Measurements of the CKM angle γ at BaBar

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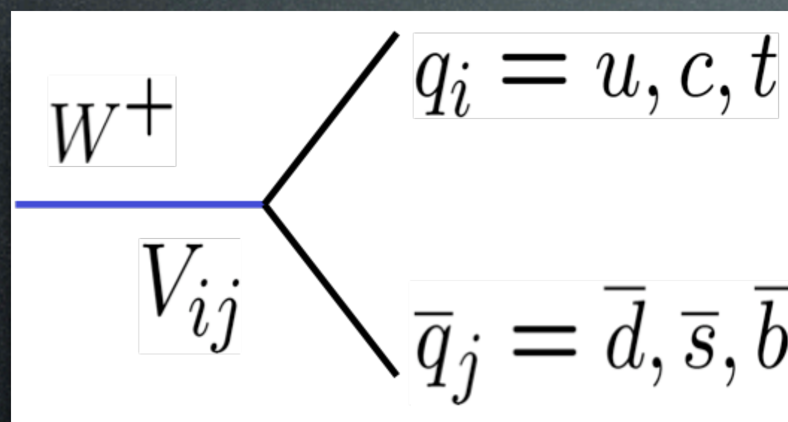
Joint Theoretical and Experimental Physics Seminar
Fermilab, April 17 2009

Outline

- CP violation in the SM
- How can we measure it at B factories
- The angle γ of the Unitary Triangle
- BaBar's adventures in γ land
- Selected results
- Outlook

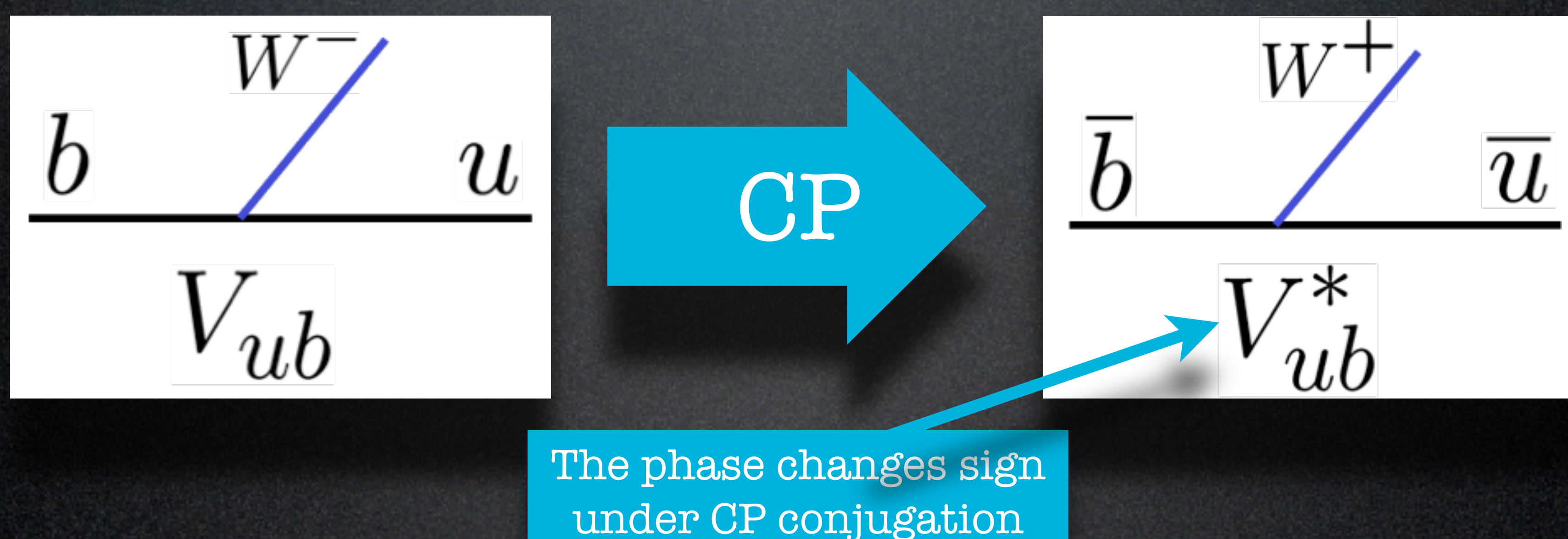
The CKM matrix

- In the Standard Model, the CKM matrix elements Vij describe the electroweak coupling strength of the W to quarks
  - CKM mechanism describes quark flavor mixing



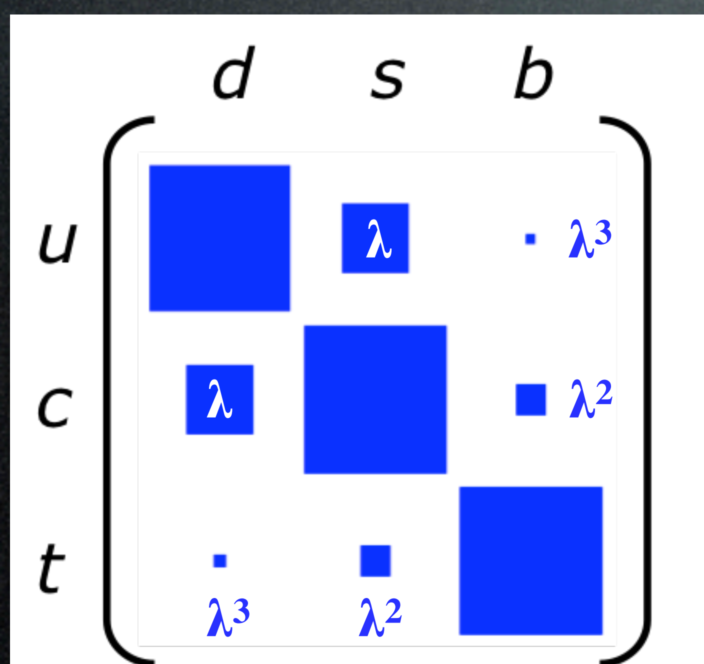
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

  - Complex phases in V_{ij} are the origin of SM CP violation



The CKM matrix

- The CKM matrix V_{ij} is unitary with 4 independent fundamental parameters (including 1 irreducible complex phase)
  - Magnitude of elements strongly ranked (leading to ~diagonal form)
  - Choice of overall complex phase arbitrary – only V_{td} and V_{ub} have non-zero complex phases in Wolfenstein convention



$\lambda = \sin(\theta_c) = 0.22$

$$\begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{pmatrix}$$

Some of the real elements in the Wolfenstein convention may have small $O(\lambda^4)$ complex phases

- Measuring SM CP violation → Measure complex phase of CKM elements

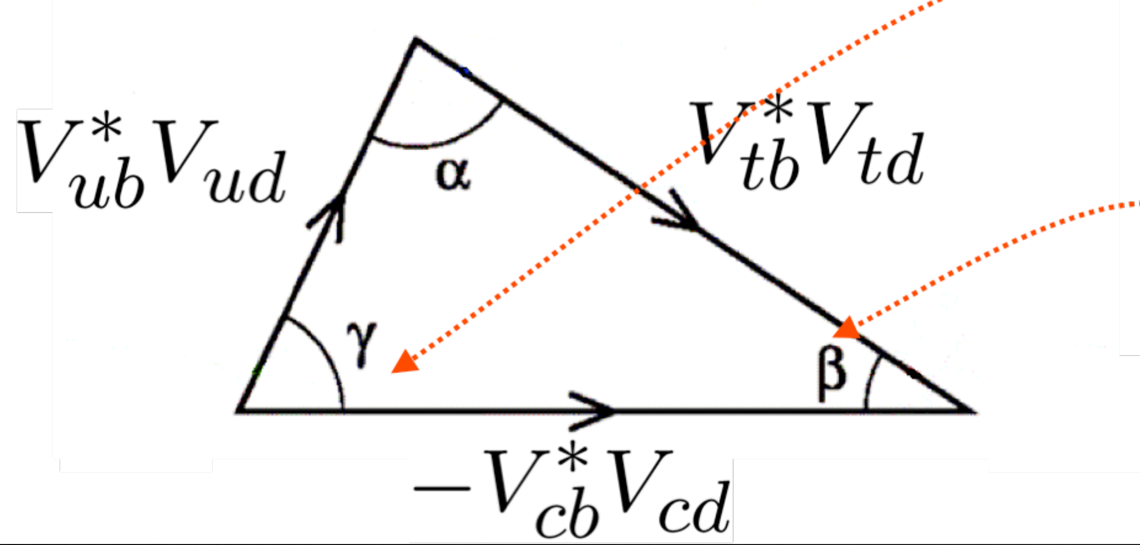
The Unitarity Triangle

- Among the unitarity conditions, the following one is related to CP violation in the B_d system, and promises the largest CP violation:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

- Visualization in the complex plane: β and γ are two angles of a triangle.

- Surface of triangle is proportional to amount of CPV introduced by CKM mechanism

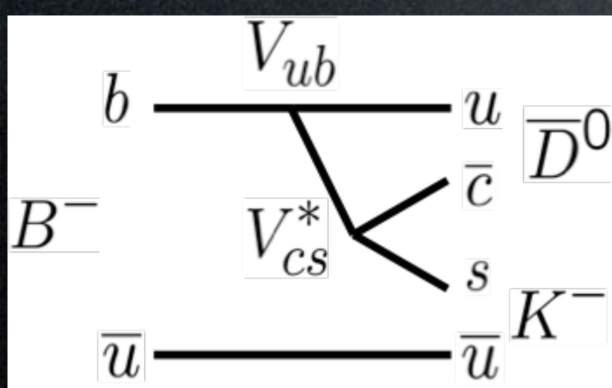


$$\begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{pmatrix}$$

$$\gamma = arg\left[-\frac{V_{ub}^*V_{ud}}{V_{cb}^*V_{cd}}\right]$$

Amplitudes phases and observables

- How do complex phases affect decay rates
  - Only affects decays with more than 1 amplitude
  - Decay rate $|A|^2 \rightarrow$ phase of sole amplitude does not affect rate
- Consider case with 2 amplitudes with same initial and final state: decay rate $|A_1 + A_2|^2$



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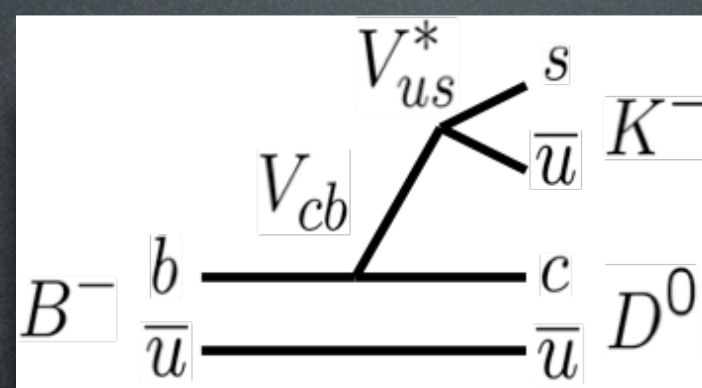
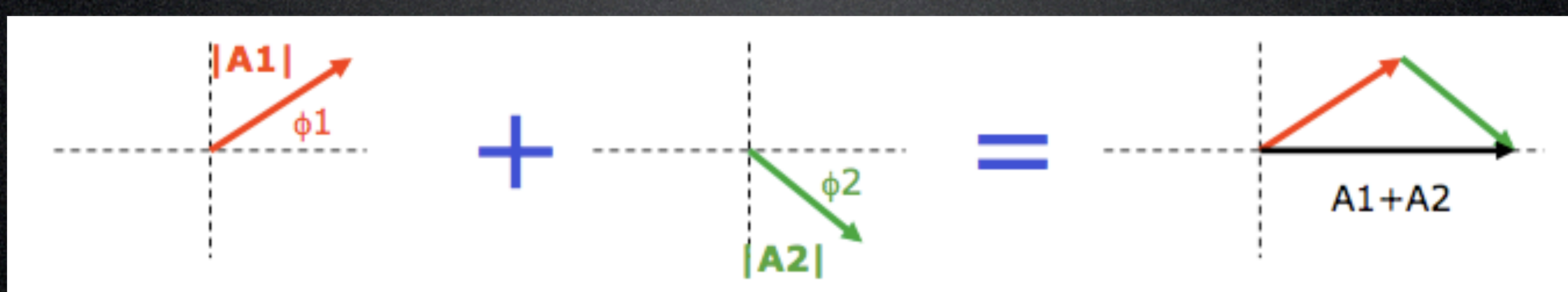
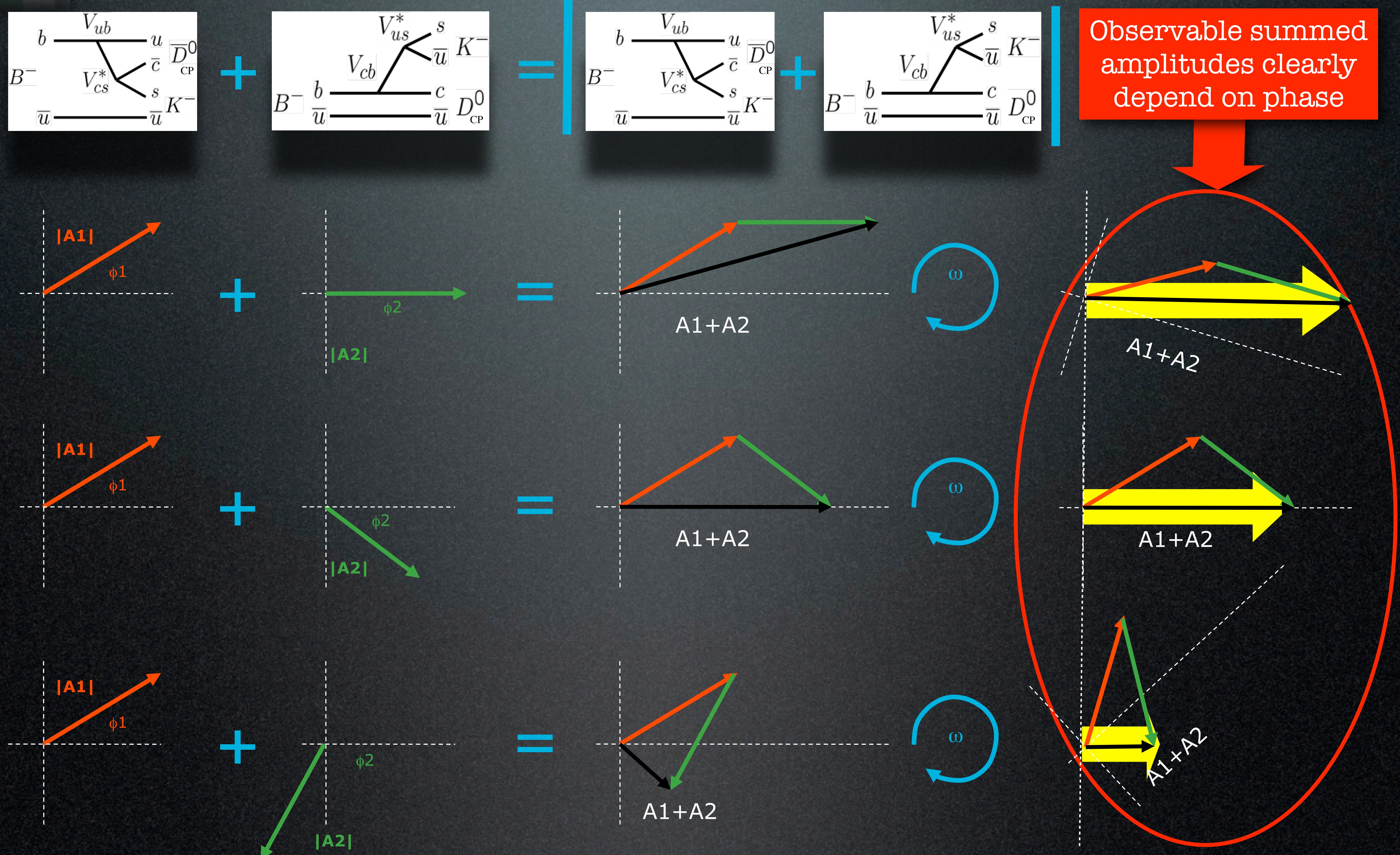


$$\left| A_1 + A_2 \right|^2 = |A_1|^2 + |A_2|^2 + 2|A_1||A_2| \cos(\phi_1 - \phi_2)$$

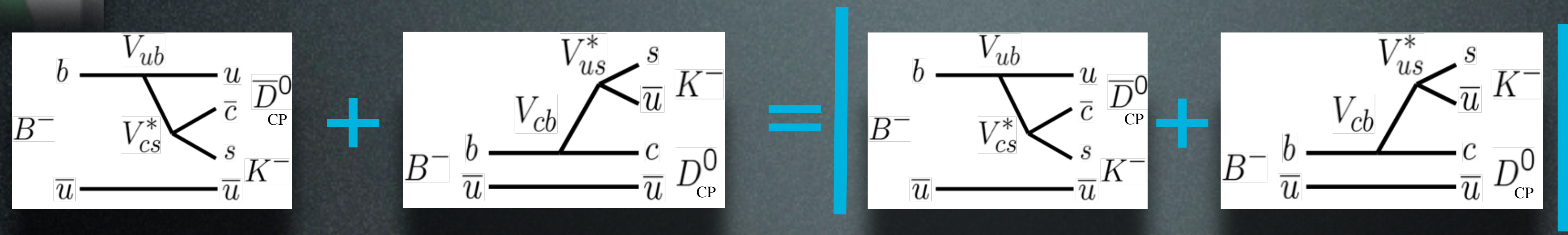
$A_1 = |A_1| e^{i\phi_1}$ $A_2 = |A_2| e^{i\phi_2}$



Phases and observables



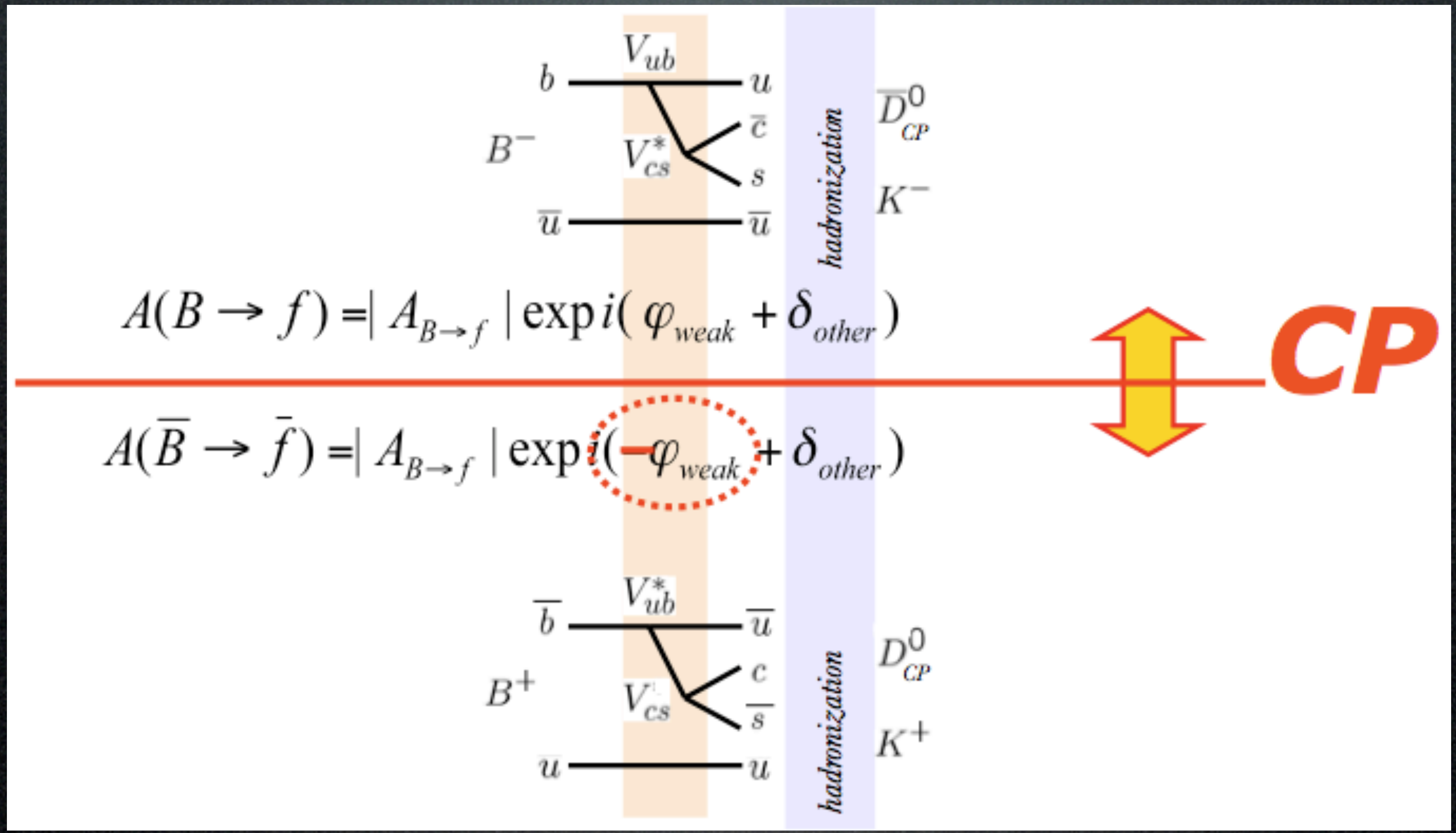
Amplitudes and observables



Dependence on $\Delta\Phi$ scales with magnitude ratios

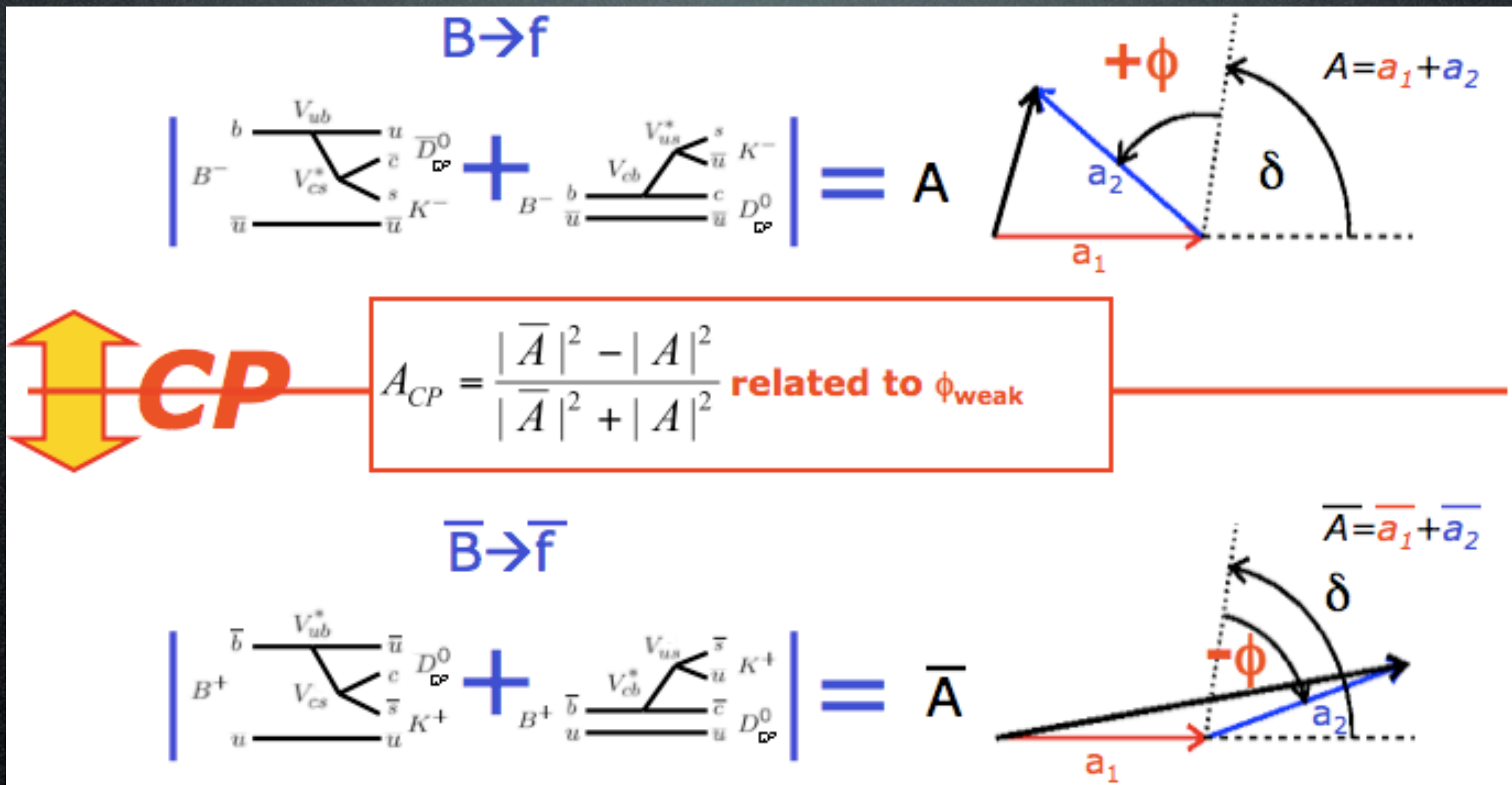
Measuring CKM phases with CP violation

- Decay rate of interfering amplitudes sensitive to phase difference
  - How to disentangle weak phase from overall phase difference between amplitudes?
- Exploit weak phase sign flip under CP transformation
  - Look at decay rates for $B \rightarrow f$ and for $\bar{B} \longrightarrow \bar{f}$



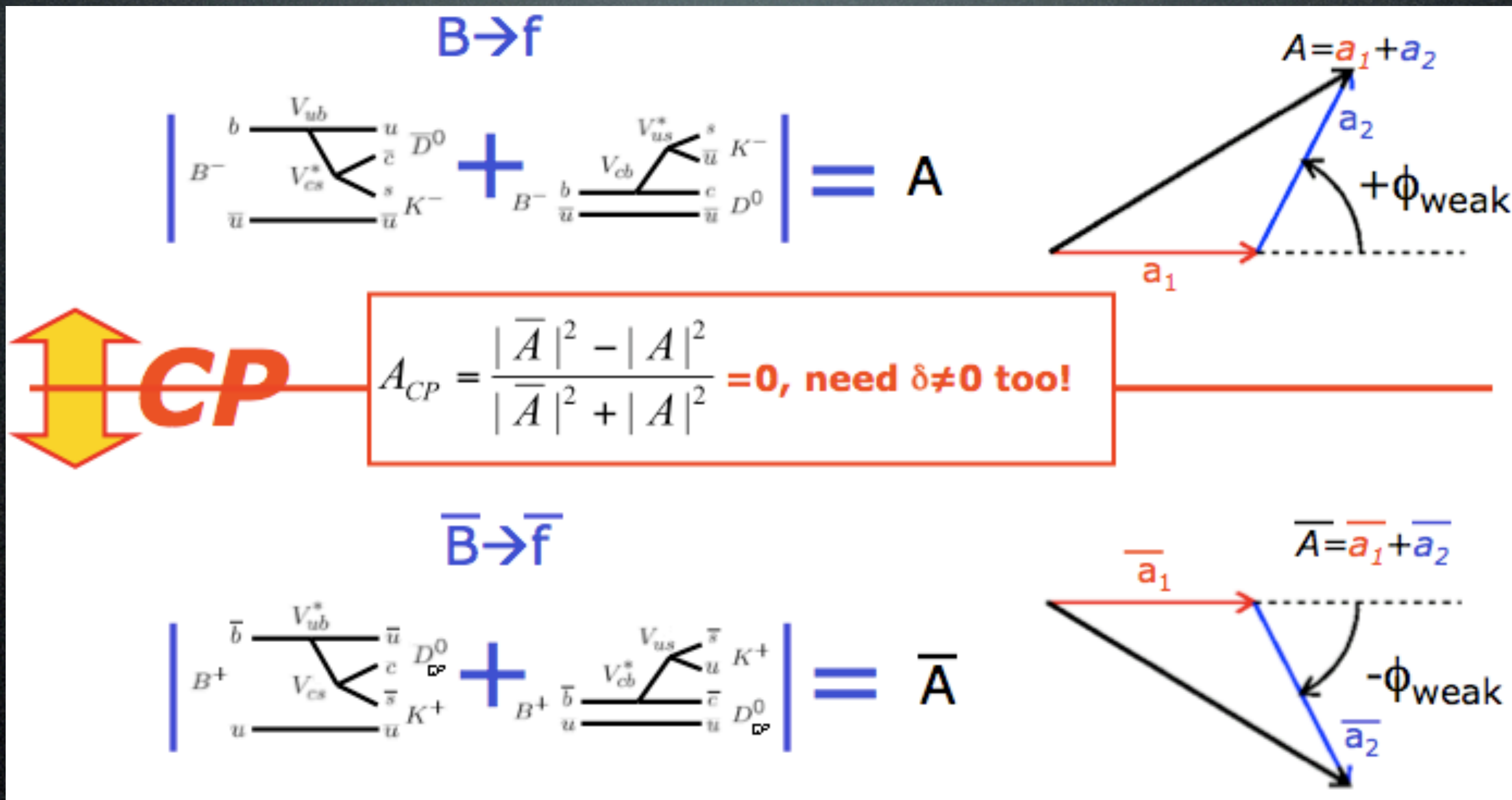
Observable CP violation by weak phase

- Effect of weak phase sign flip on interfering amplitudes



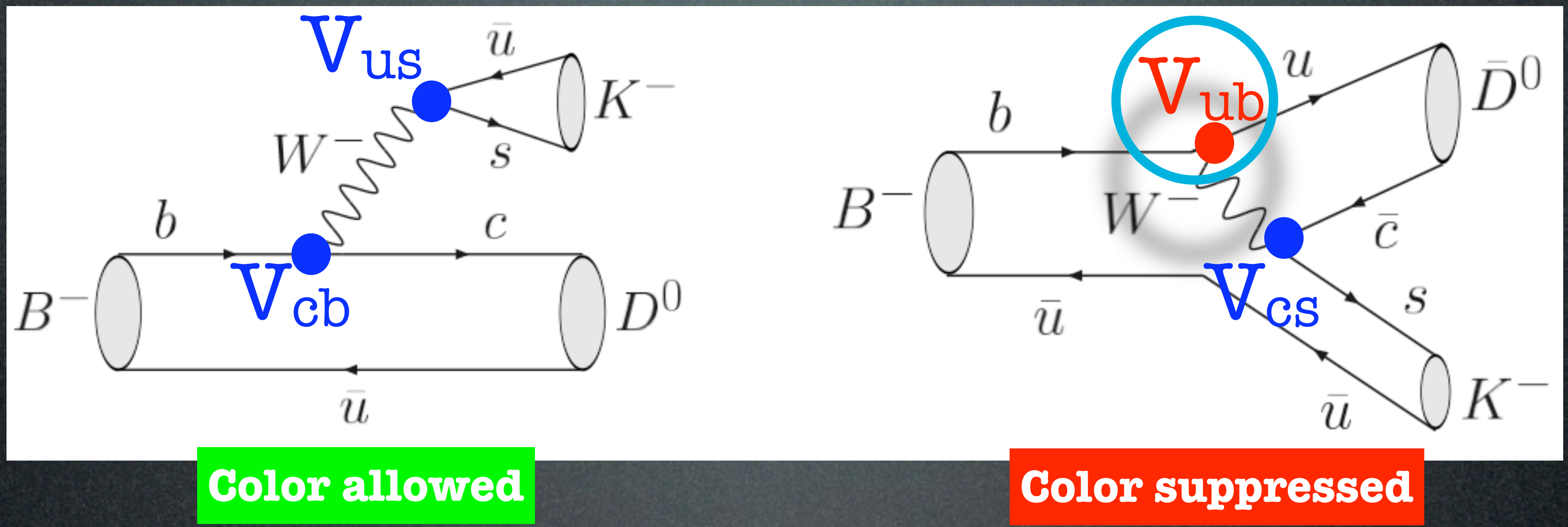
But not always...

- Effect of weak phase sign flip on interfering amplitudes



Measuring the CKM angle γ

- Among several theoretical approaches the cleanest one is using charged $B^{\pm} \rightarrow D^0 K^{\pm}$ (tree) decays:



- D^0 and $\bar{D}^0$ decay to the same final state to allow interference
- Only weak phase is in V_{ub} so phase difference is γ

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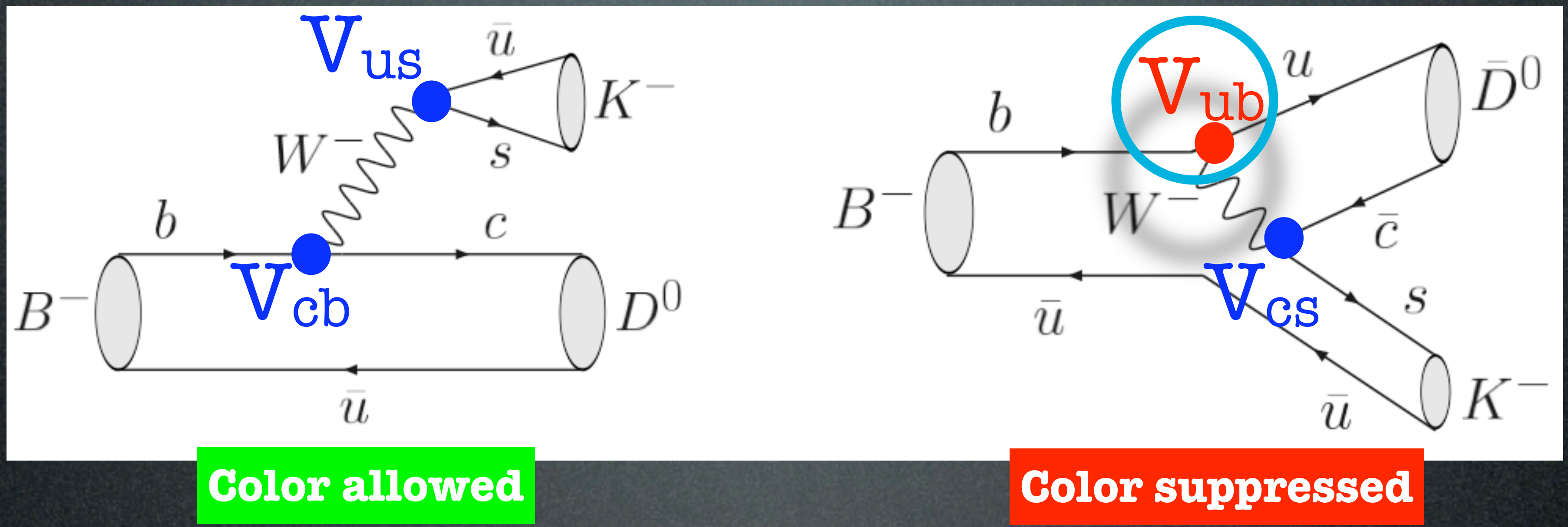

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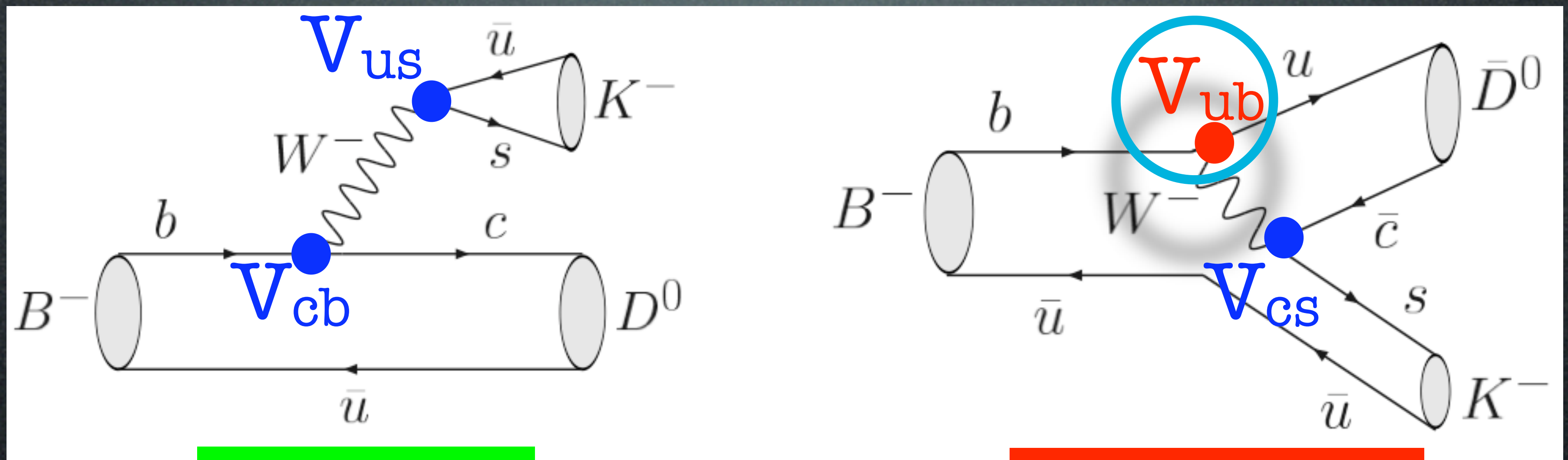

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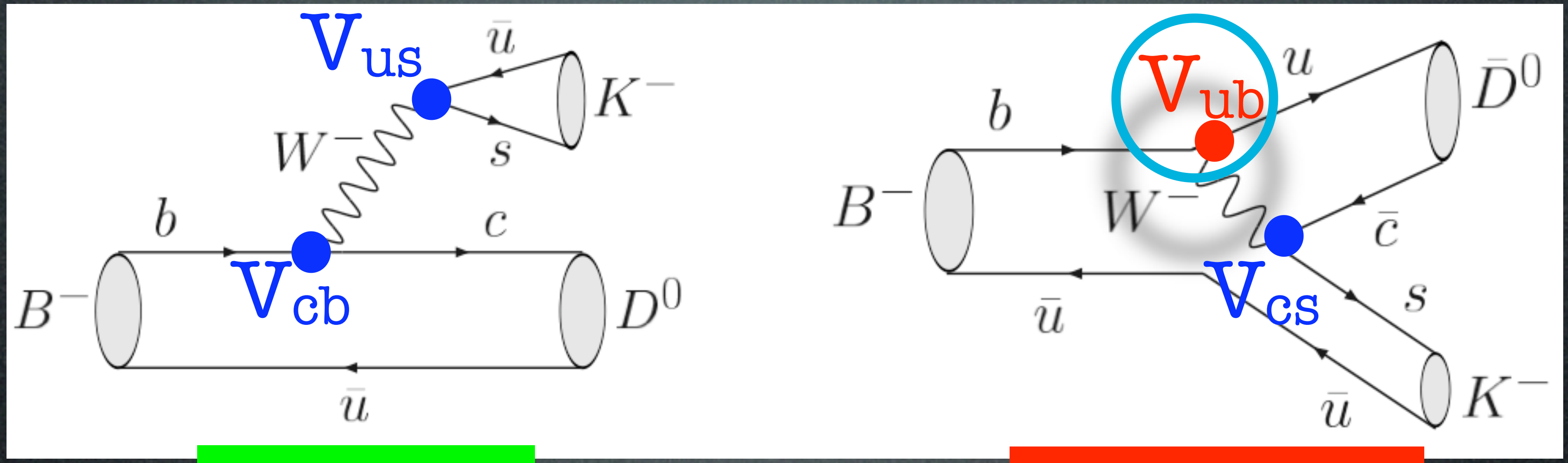

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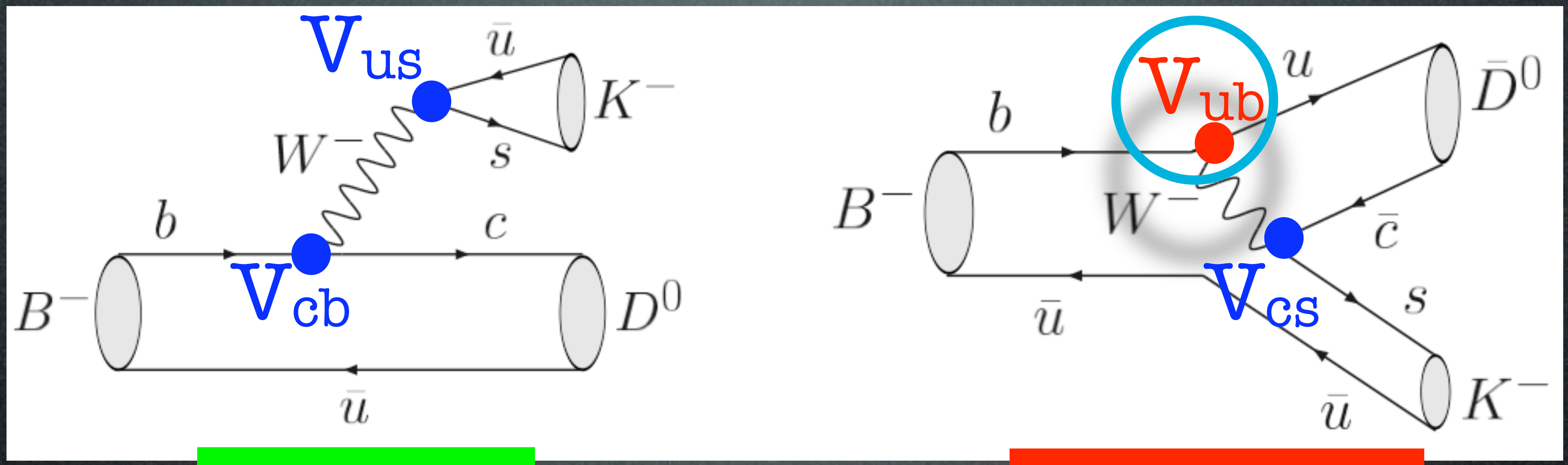

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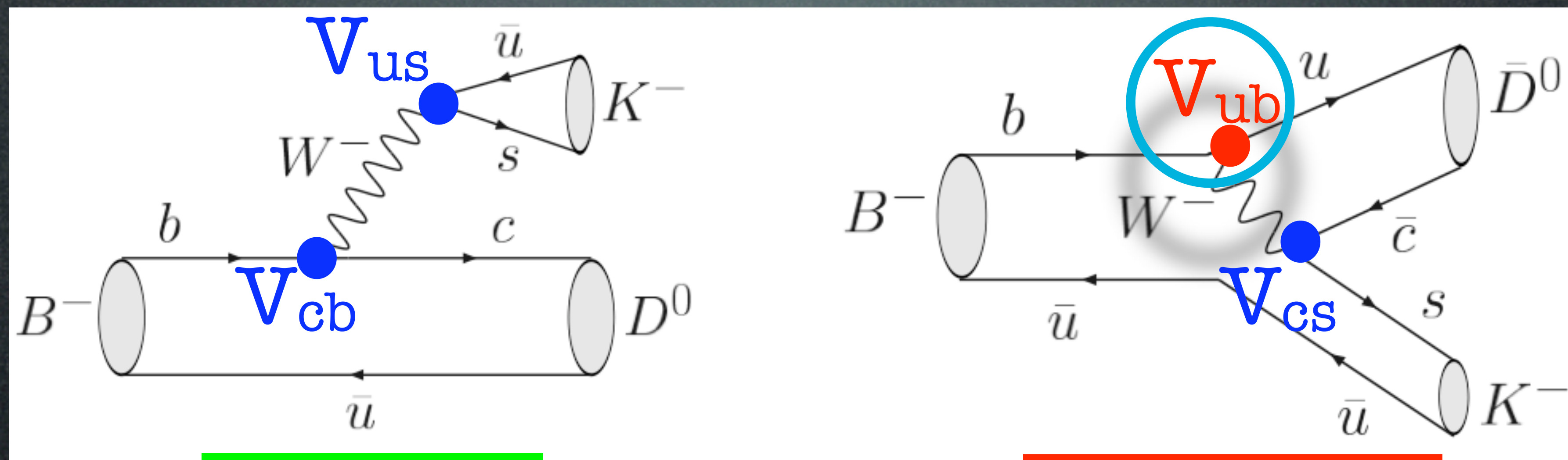

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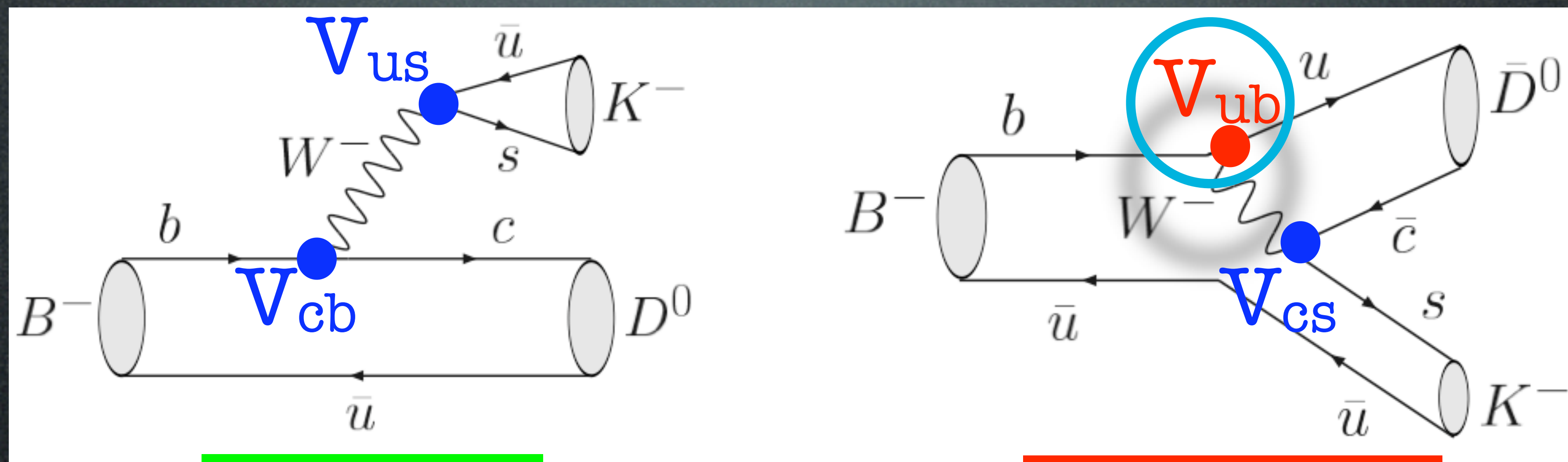

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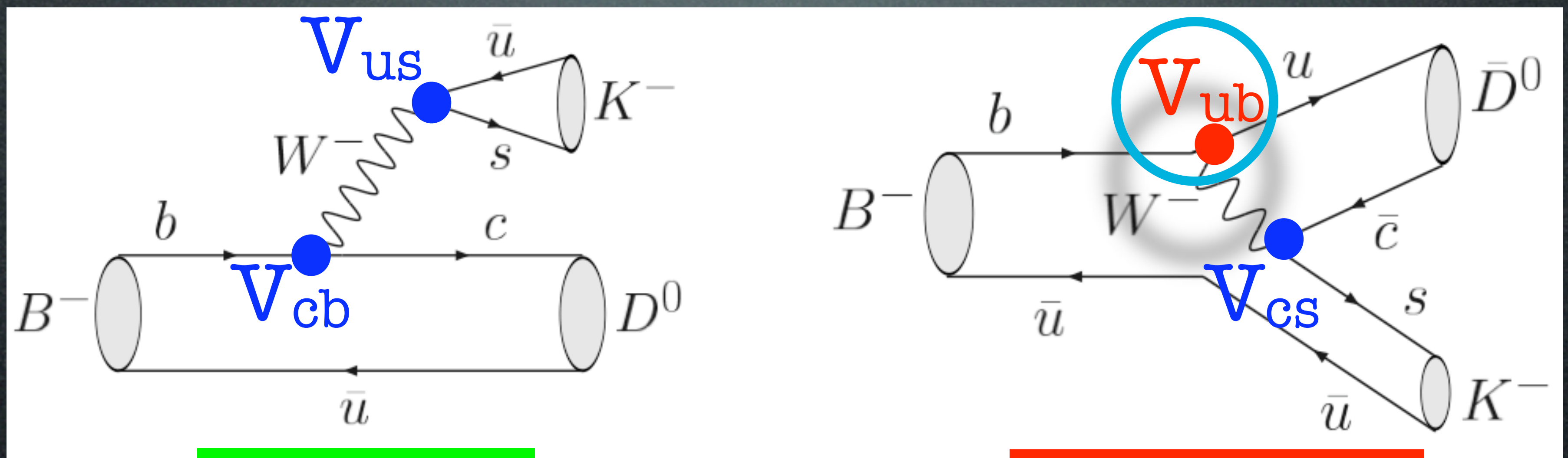

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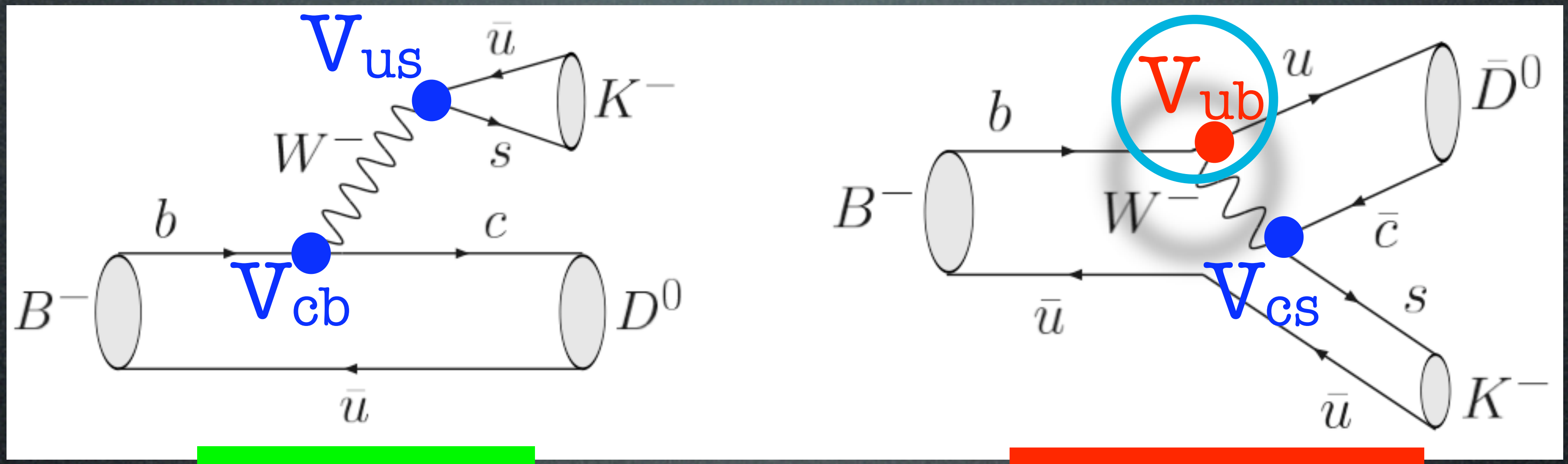

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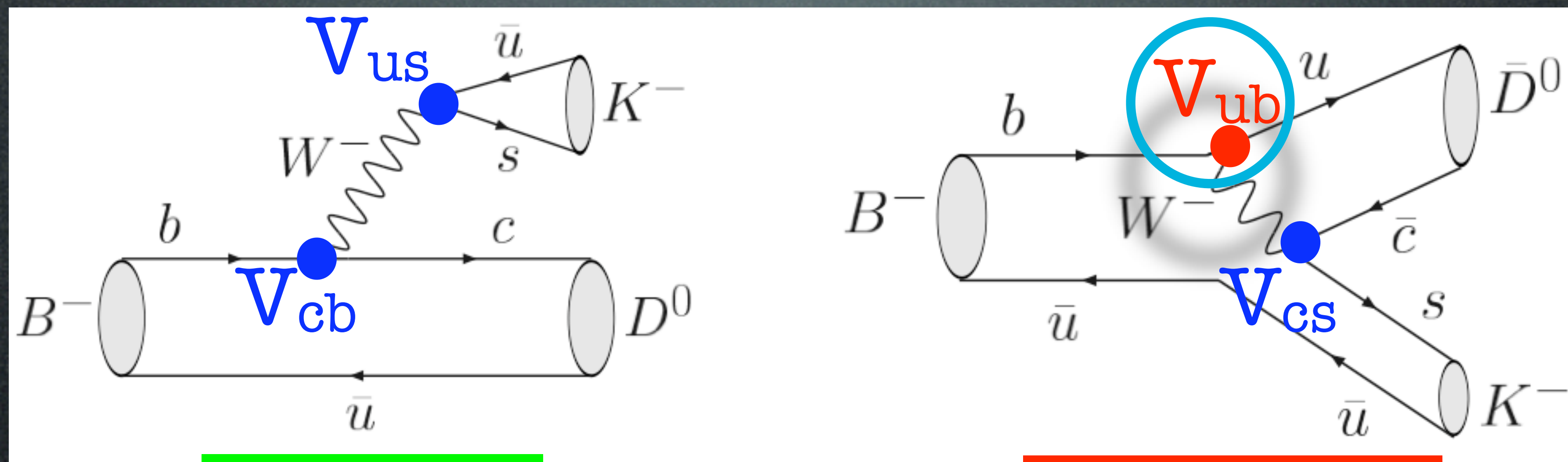

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λ^3

$$r_B \equiv \left| \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)} \right| \approx 0.1$$

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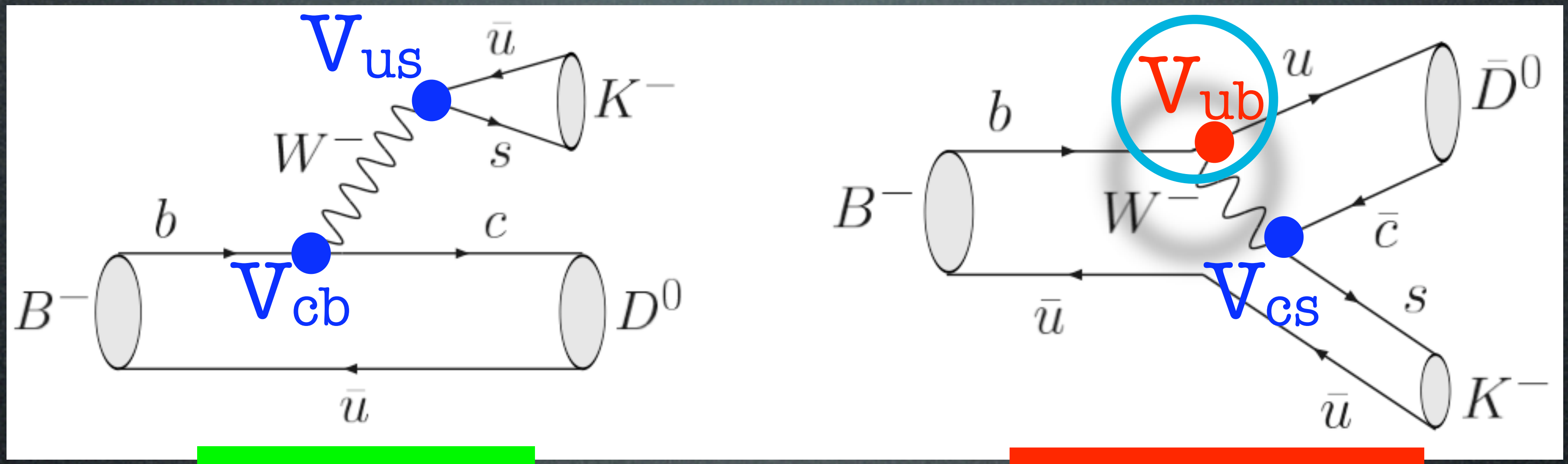

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- Neglect D^0 - $\bar{D}^0$ mixing and CPV in D decays
- B decay hadronic parameters to be determined experimentally:
  - strong phase of B decay: δ_B
  - B decay amplitudes magnitude ratio: $r_B = |A(b \to u)/A(b \to c)| \simeq 0.1$
- Very low branching ratios (10^{-5}-10^{-7}) due to CKM suppression
- Largely unaffected by new physics (tree level)

Measuring the CKM angle γ

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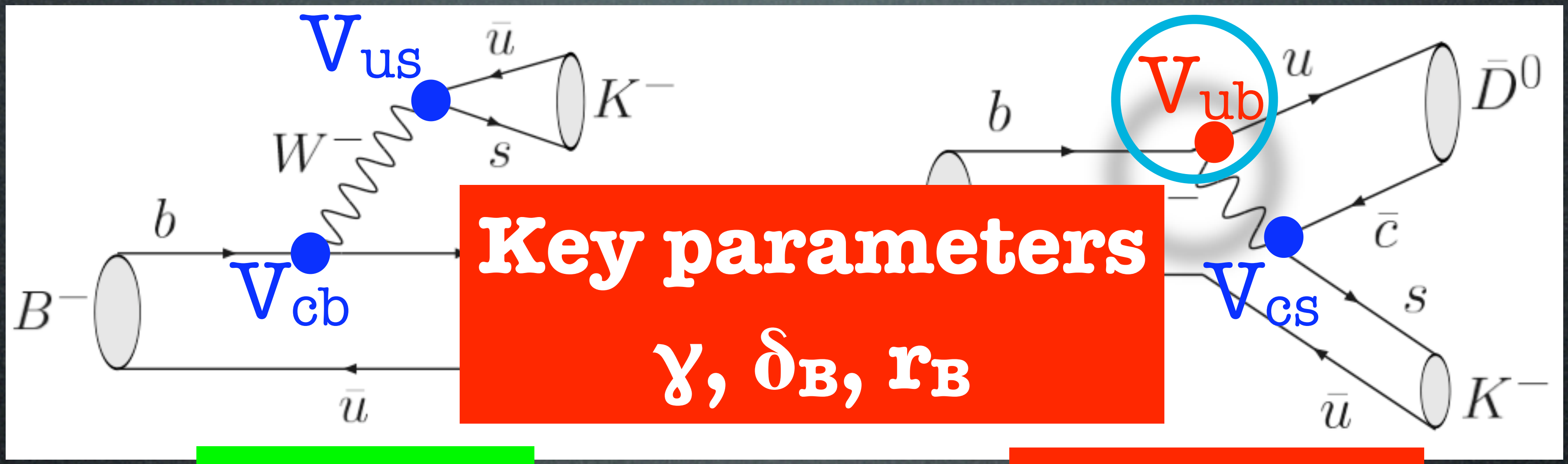

Key parameters

γ, δ_B, r_B

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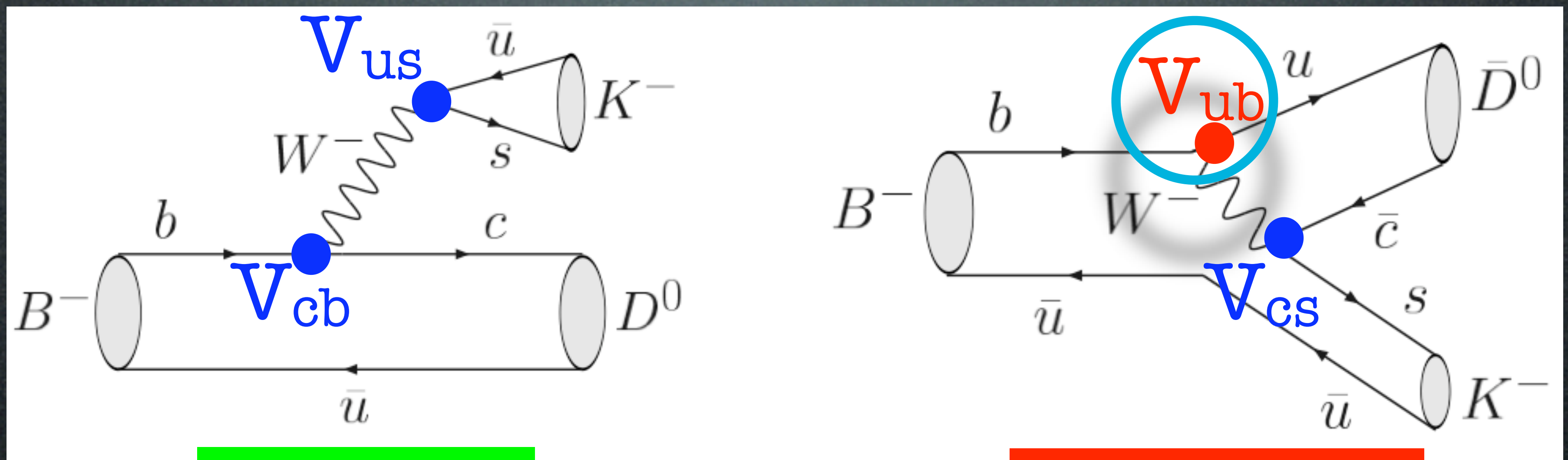
Measuring the CKM angle γ

- Select final states that enhance interference (large strong phases preferred)



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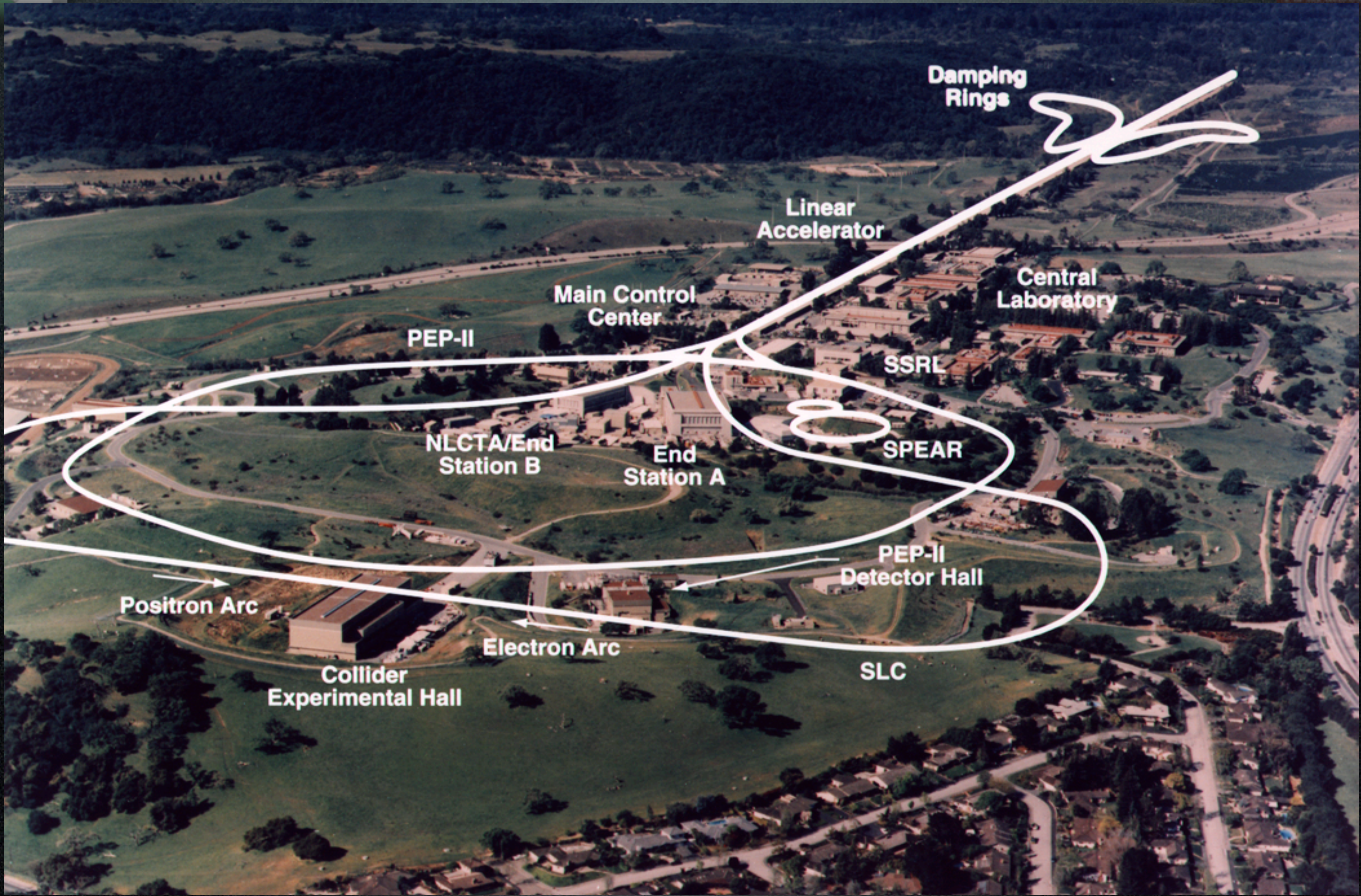
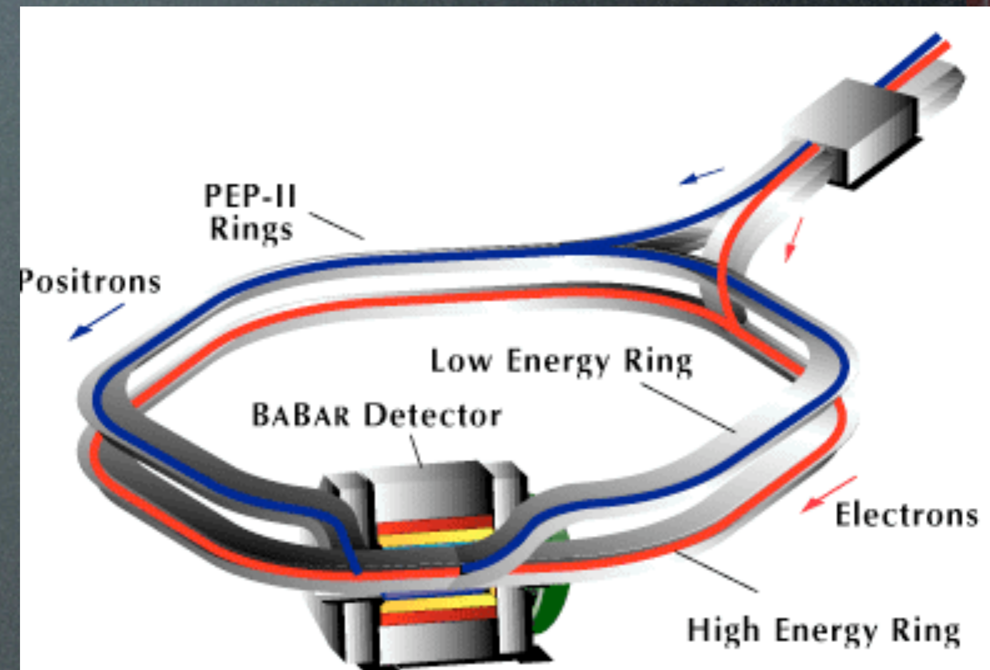
- Based on the final state of the D^0 decay there are three methods:
  - CP eigenstates ($\pi^+\pi^-$, K^+K^-, $K_S\pi^0$) **GLW**
  - Doubly Cabibbo Suppressed transitions ($K^+\pi^-$) **ADS**
  - Three body decays ($K_S\,\pi^+\pi^-$, $K_SK^+K^-$) **Dalitz-plot**
- All methods access the same hadronic parameters and gamma
- For each method various B (charged and neutral) decays can be used:
  - $B \to D^0K$, $B \to D^{*0}K$, $B \to D^0K^*$
  - Different hadronic parameters for each B decay mode

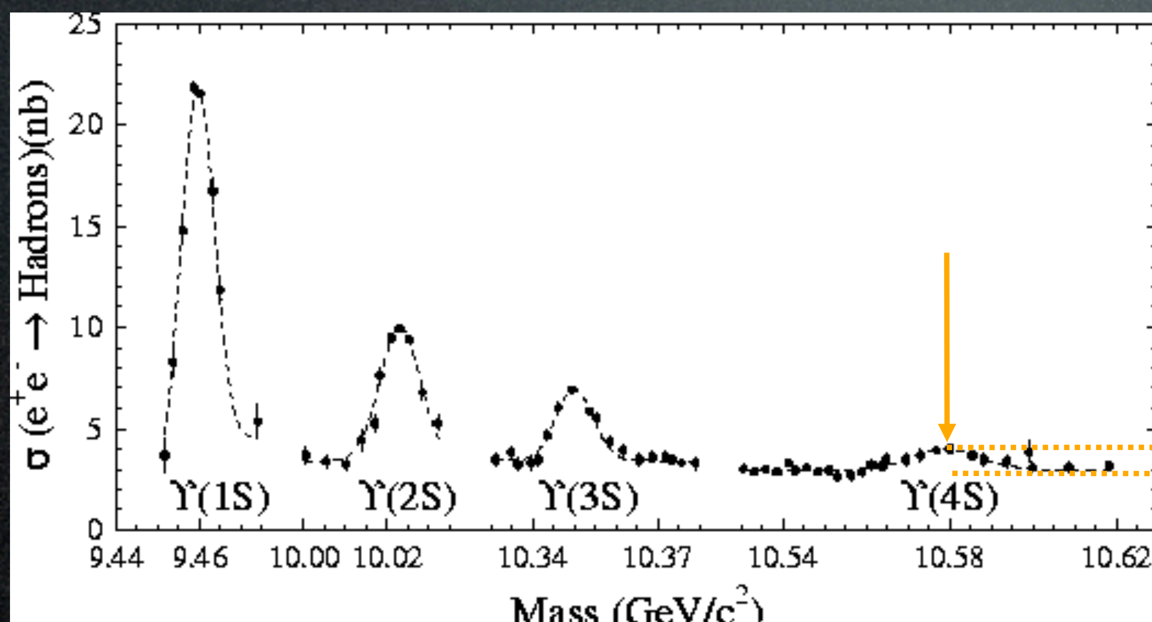
PEP-II Asymmetric B-Factory



PEP-II B-Factory

- B mesons provide an ideal playground to test the quark flavor sector of the Standard Model
- $B^0\bar{B}^0$ and B^+B^- pairs via e+e- collisions at $\Upsilon(4s)$ resonance (10.58 GeV)



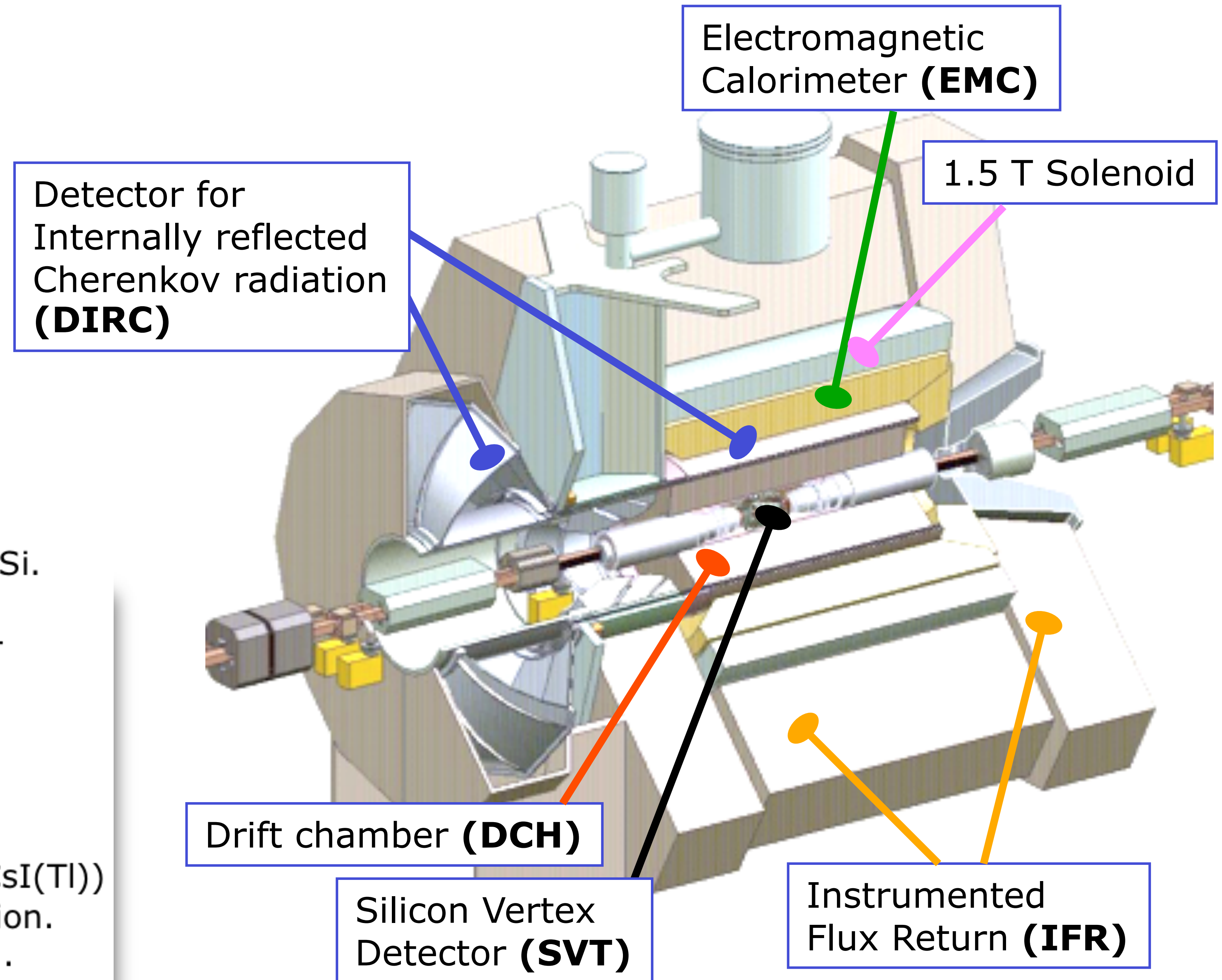


$\frac{\sigma_{b\bar{b}}}{\sigma_{hadr}}$ □ .

- 50% $B^0\bar{B}^0$, 50% B^+B^-
- Full (Run1-7) BaBar dataset of 465 Million $B\bar{B}$ pairs
- No other particles are produced in Upsilon(4S) decay: kinematic of the event can be exploited

The BaBar Experiment

- Outstanding K ID
- Precision tracking (Δt measurement)



SVT: 5 layers double-sided Si.

DCH: 40 layers in 10 super-layers, axial and stereo.

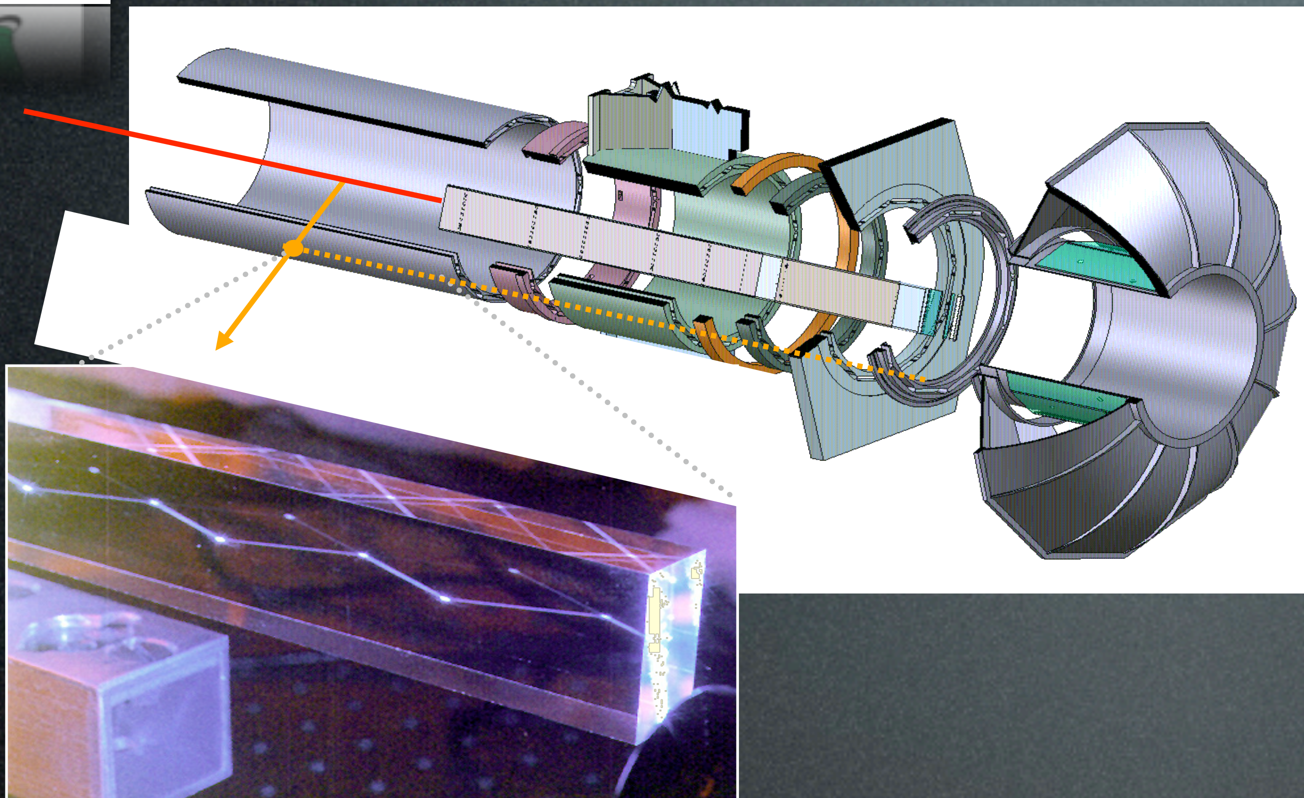
DIRC: Array of precisely machined quartz bars.

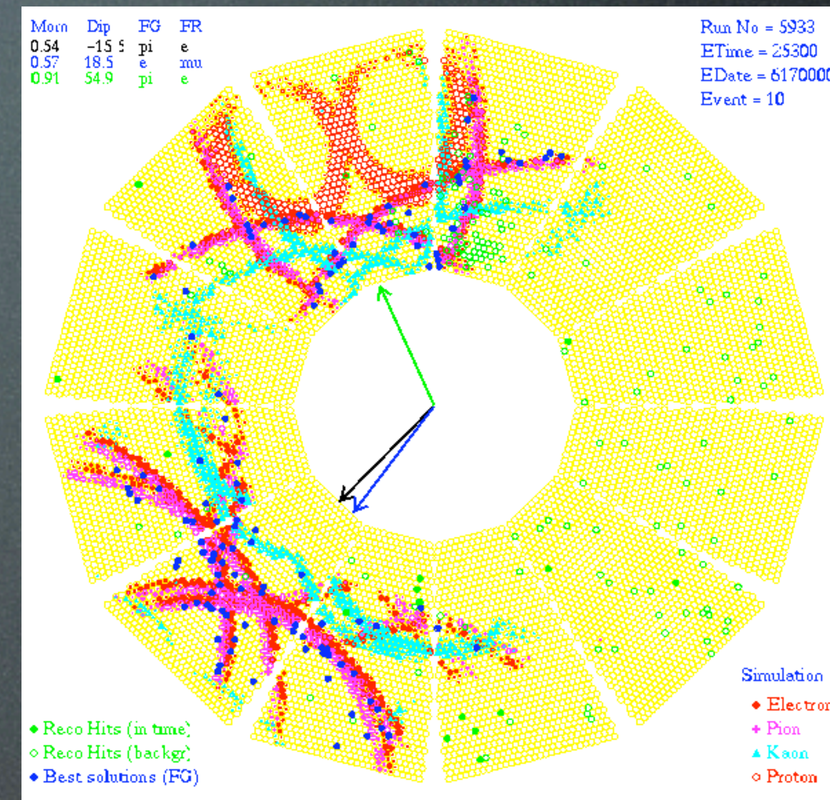
EMC: Crystal calorimeter (CsI(Tl)) Very good energy resolution. Electron ID, π^0 and γ reco.

IFR: Layers of RPCs within iron. Muon and neutral hadron (K_L)

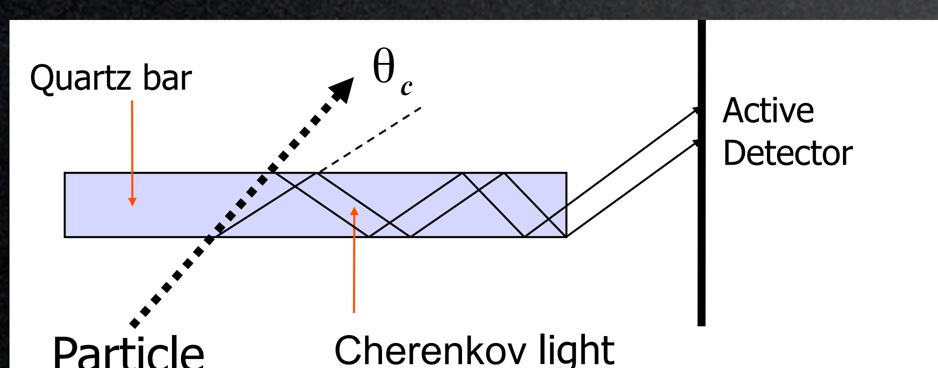
The BaBar Experiment

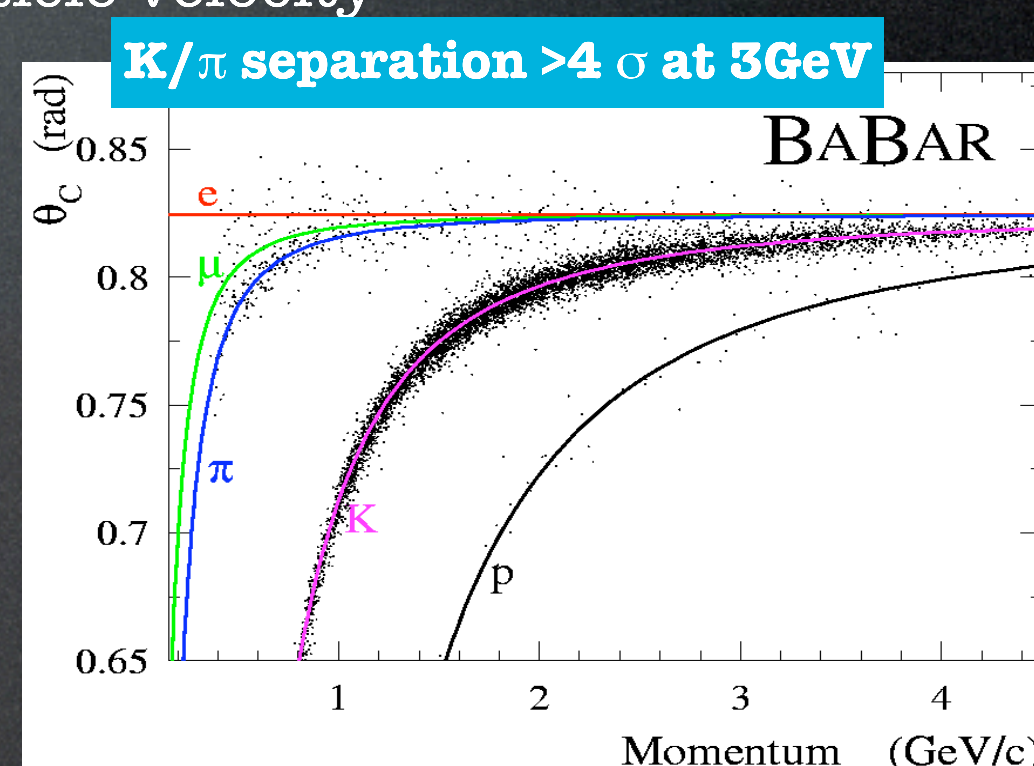
Cherenkov Particle Identification System





- Cherenkov light angle depends on particle velocity
- Transmitted by internal reflection
- Detected by more than 10000 PMTs
- Thin detector volume





Selecting B decays for CP analysis

- Principal event selection variables
  - Exploit kinematic constraints from beam energies
  - Beam energy-substituted mass has better resolution than invariant mass

Energy-substituted mass

$$m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_{B}}$$

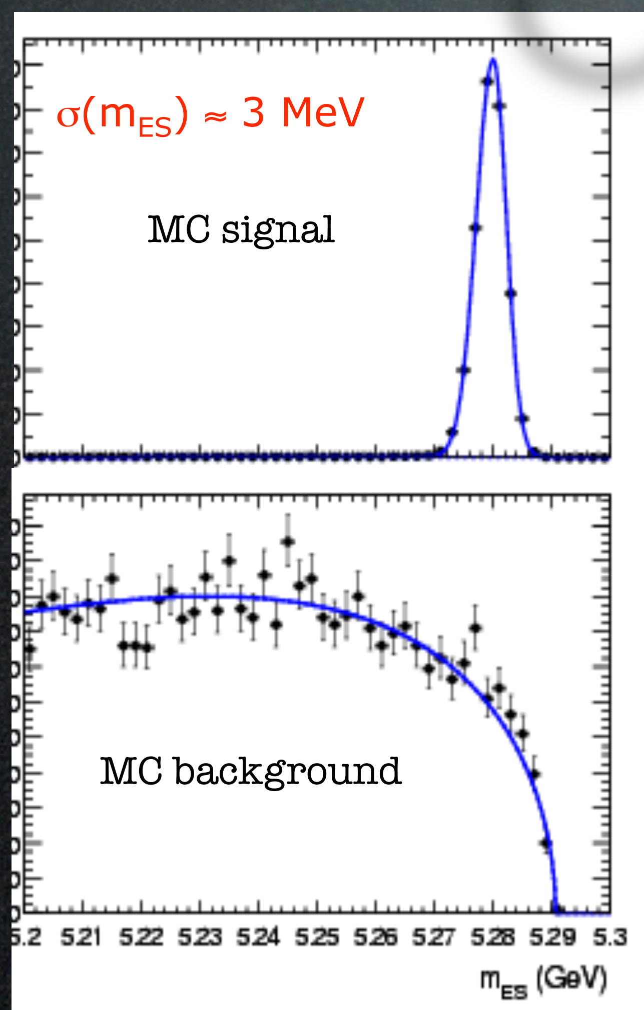
Energy difference

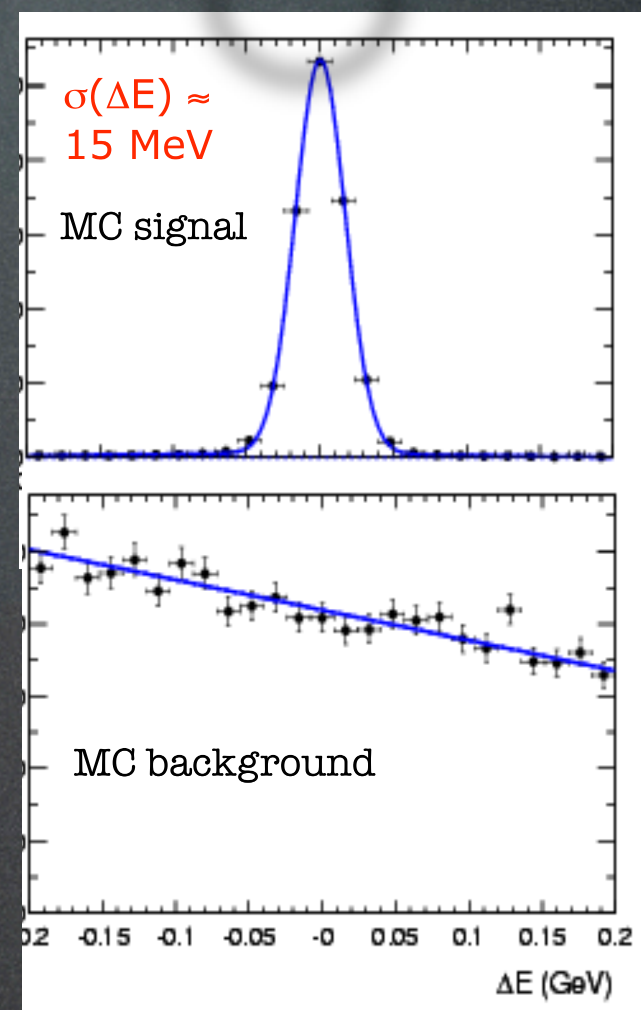
$$\Delta E = E^{*}_{B} - E^{*}_{beam}$$

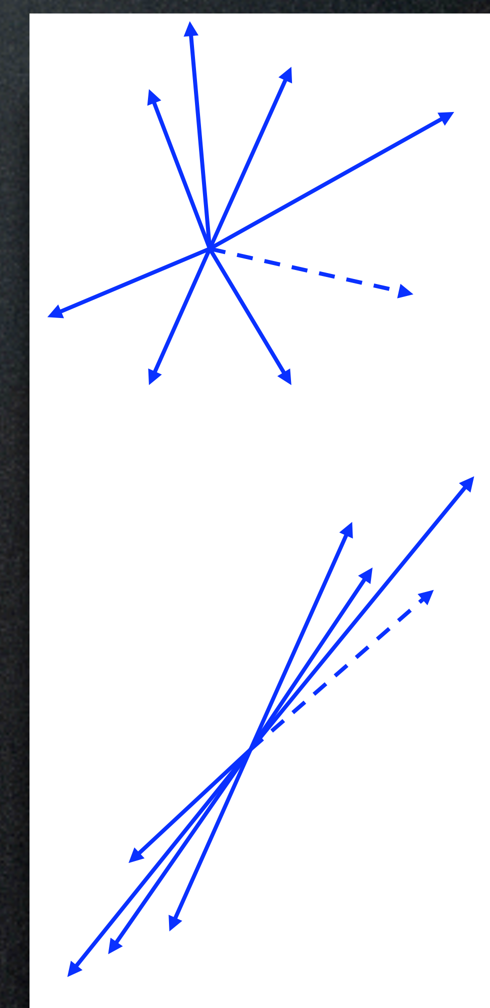
Event shape

$B\bar{B}$ events

$q\bar{q}$ events (q=u,d,s,c)



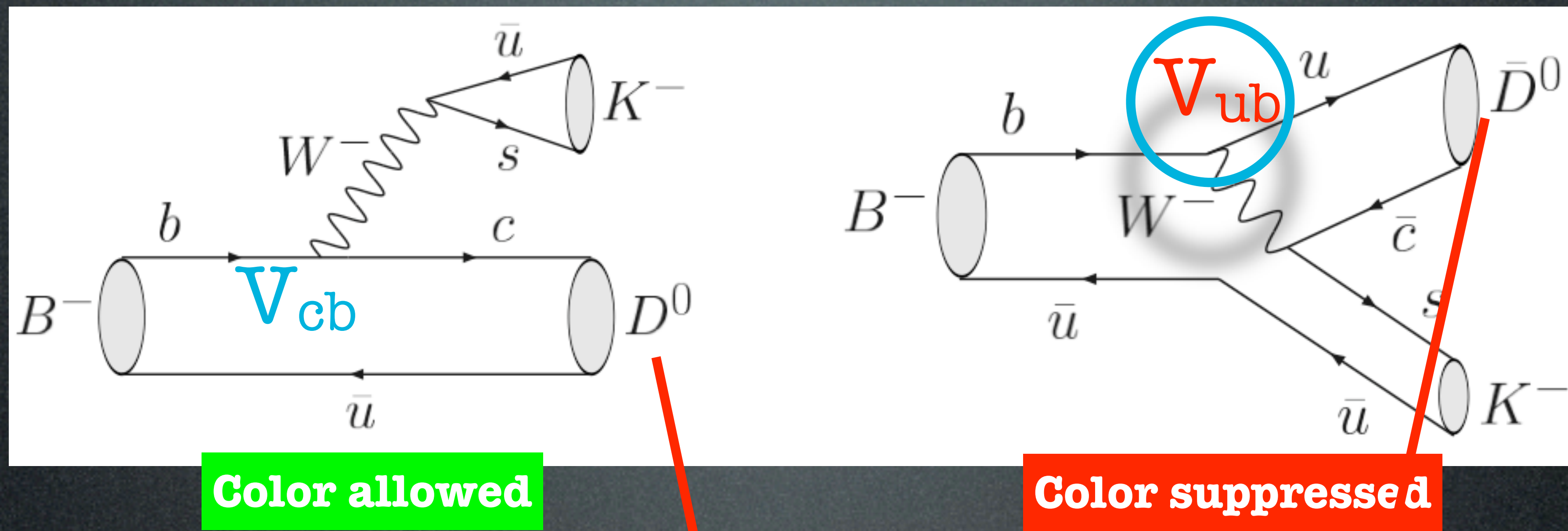




Dalitz plot method

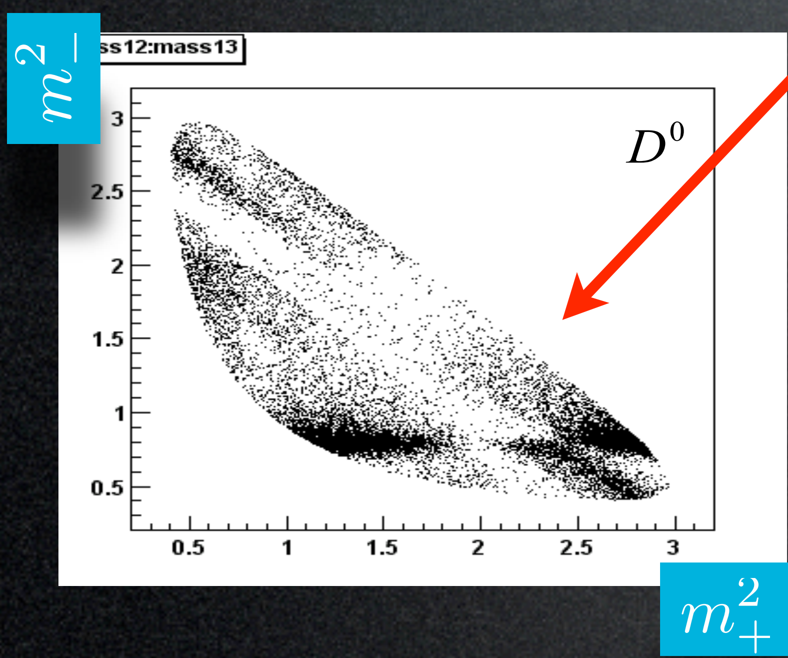
Dalitz plot method

- Neutral D meson reconstructed in 3-body self-conjugate final state ($K_S\pi^+\pi^-$ and $K_SK^+K^-$):

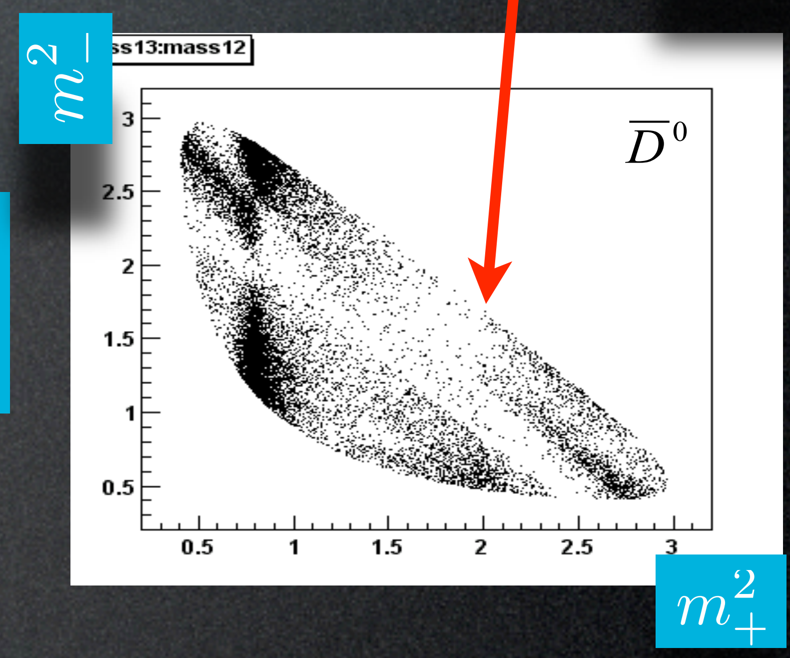


$$A_-(m_-^2, m_+^2) \propto A_{D-} + r_B e^{i(\delta_B - \gamma)} A_{D+}$$

$$m_\pm^2 = m(K_S^0\pi^\pm)^2$$



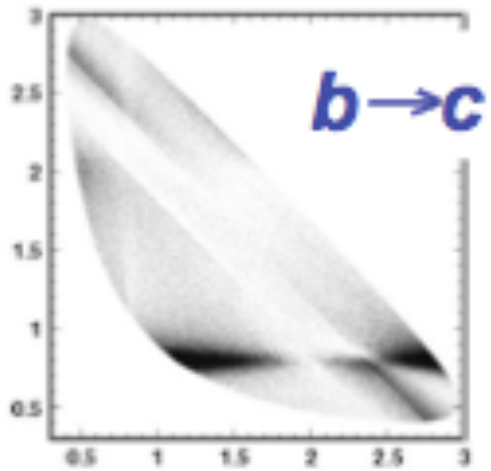
Dalitz-plot distribution from data

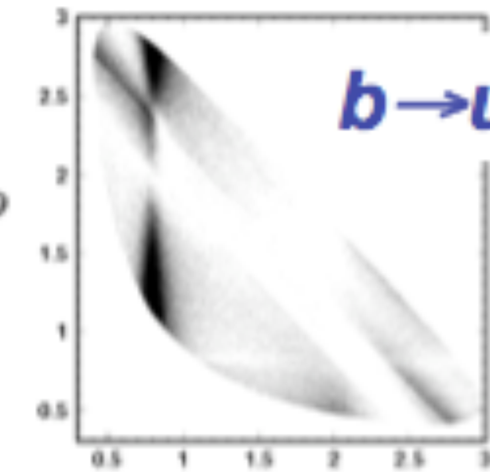


Dalitz plot method

$A(B^-)$

$$\Big(D^0 \rightarrow K^0_S \pi^+ \pi^- \quad + \; r_b \, e^{-i\gamma + i\delta_b} \quad \overline{D}^0 \rightarrow K^0_S \pi^+ \pi^- \Big)$$

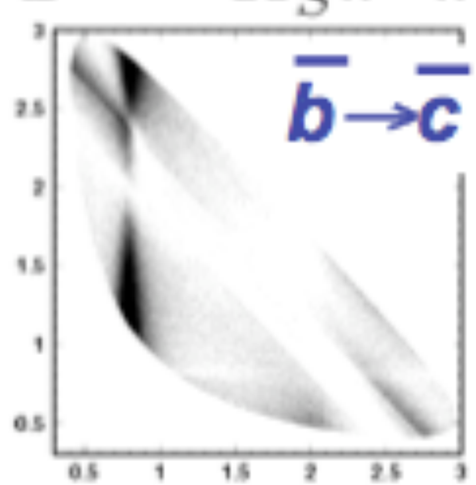


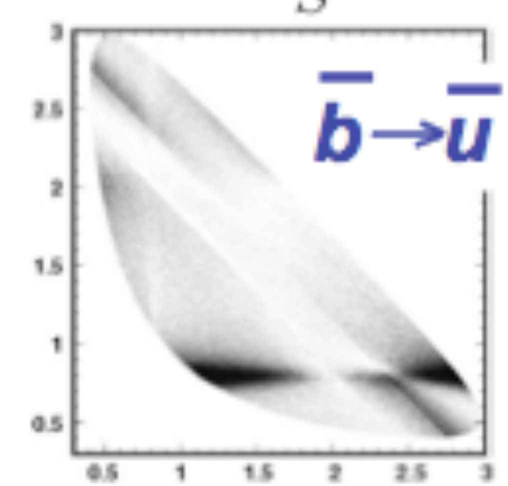


Relative weak phase γ changes sign

$A(B^+)$

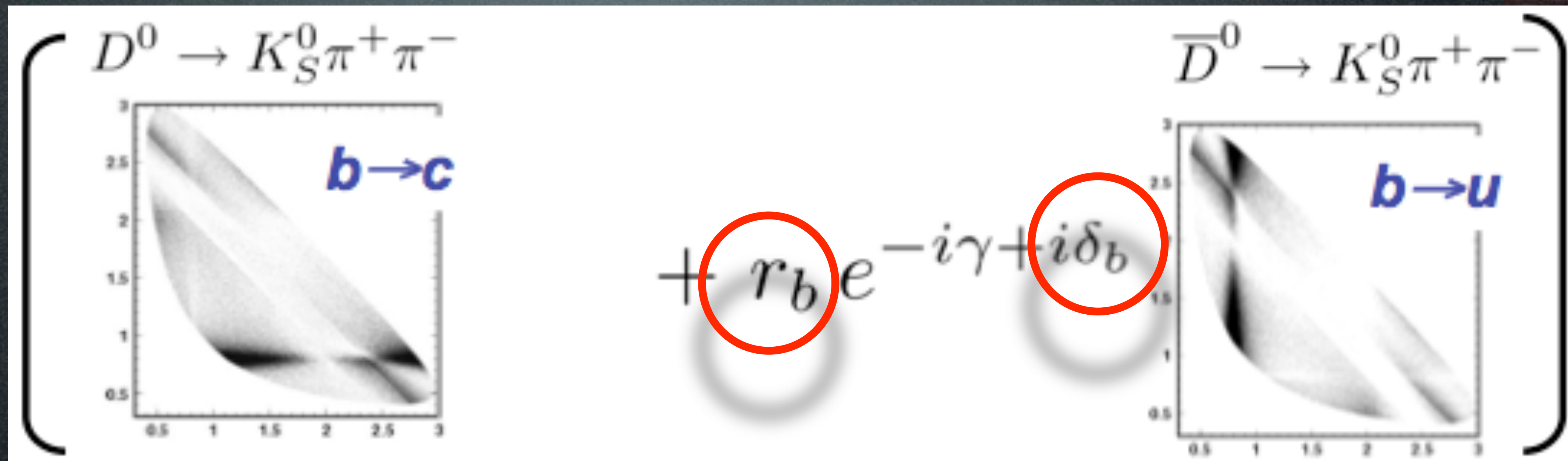
$$\Big(\overline{D}^0 \rightarrow K^0_S \pi^+ \pi^- \quad + \; r_b \, e^{+i\gamma + i\delta_b} \quad D^0 \rightarrow K^0_S \pi^+ \pi^- \Big)$$





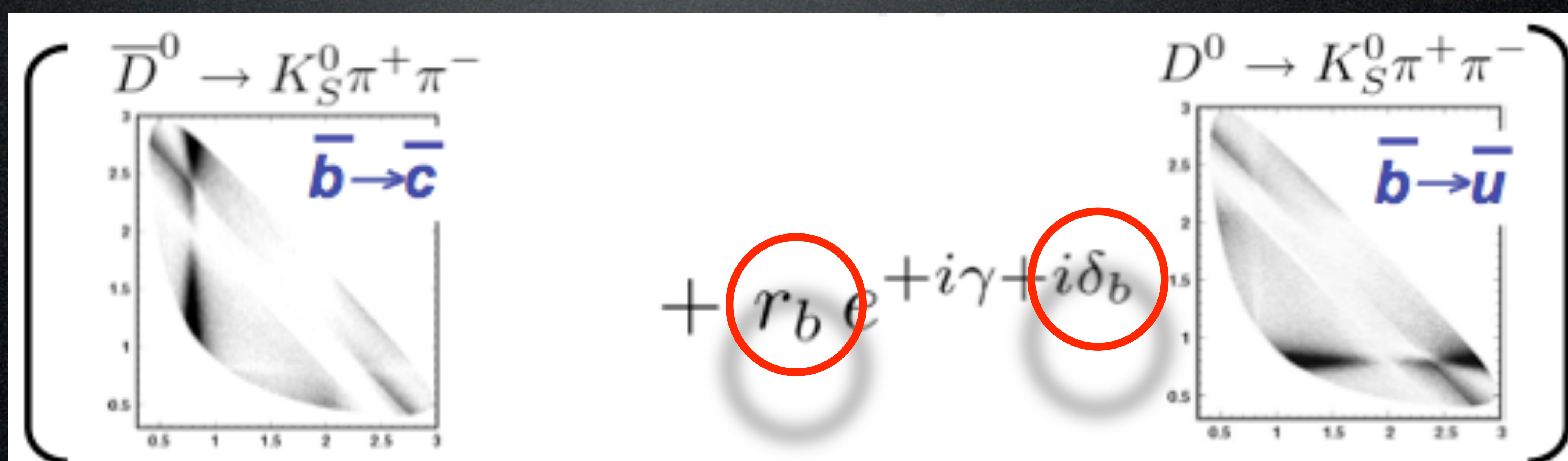
Dalitz plot method

A(B⁻)



Hadronic parameters δ_B, r_B determined from data

A(B⁺)



Dalitz plot method

- Advantages:
  - Expect large strong phases due to the presence of resonances in final state
  - Final state involves only charged particles: higher reconstruction efficiency and lower neutrals background
- Disadvantage:
  - Dalitz plot analysis of data and of a dedicated D mesons sample
- Experimentally access γ via decay rate (Dalitz plot distribution for signal events):

$$\Gamma_-(m_-^2, m_+^2) \propto |A_{D-}|^2 + r_B^2|A_{D+}|^2 + 2[x_- \Re\{A_{D-}A_{D+}^*\} + y_- \Im\{A_{D-}A_{D+}^*\}]$$

$$x_\pm = r_B \cos(\delta_B \pm \gamma) \qquad y_\pm = r_B \sin(\delta_B \pm \gamma)$$

- Extract γ (r_B and δ_B) from fit to Dalitz-plot distribution of $m_\pm = m(K_S h^\pm)$
- The $D^0/\bar{D}^0 \to K_S^0 h^- h^+$ decay amplitudes $A_{D\mp}$ in the Dalitz plot must be known

Dalitz method

- Experimentally:
  1. Signal selection and likelihood fit (mES, ΔE and shape variables) to estimate yields and PDFs parameters
  2. $A_{D\mp}$ determined from $D^{*+} \to D^0\pi^+$, $D^0 \to K_S h^+ h^-$ control samples
  3. Likelihood fit (m_-^2,m_+^2 added) to extract x,y from the signal events
  - Use $B \to D^{(*)}\pi^0$ and $B \to D^0 a_1$ as control samples

- Two D^0 decay channels: two Dalitz plot models

- Several B decays:
  - $B^\pm \to D^0K^\pm$,
  - $B^\pm \to D^{*0}K^\pm$ (both $D^{*0} \to D^0\pi^0$ and $D^{*0}\gamma$),
  - $B^\pm \to D^0K^{*\pm}$($K_SK^+K^-$ not considered in D^0K^*)
  - This implies different r_B, δ_B and consequently $x_\pm$,$y_\pm$

- Importance of reaching gamma from different channels

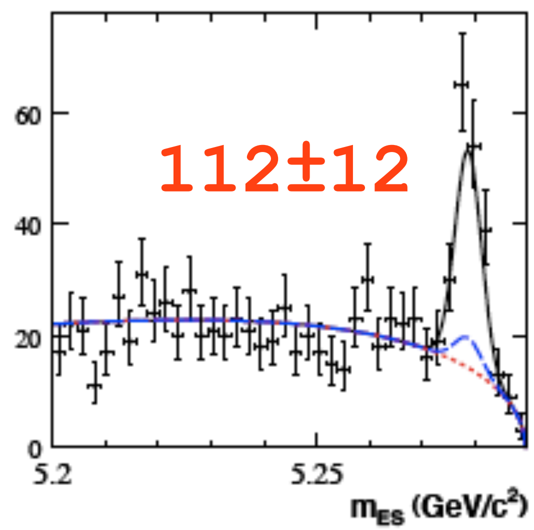
Dalitz-plot signal selection

$N_{BB} = 383\text{x}10^6$

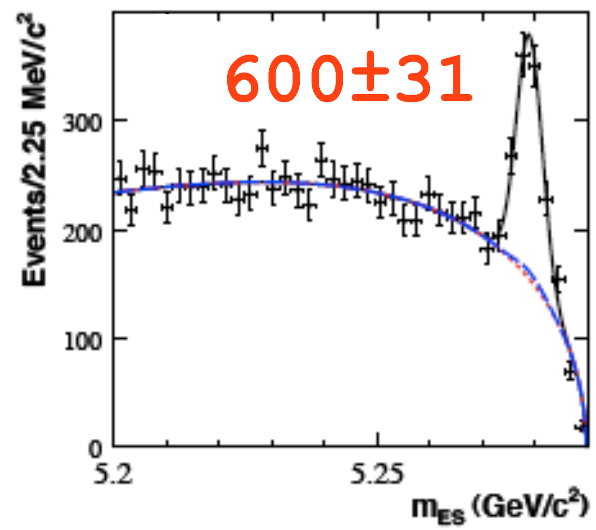
163 $D^0 \rightarrow K_sKK$ ev. new! → 979 $D^0 \rightarrow K_s\pi\pi$ events

First step:
signal selection
ML fit to
kinematic and
angular
variables to
extract yields

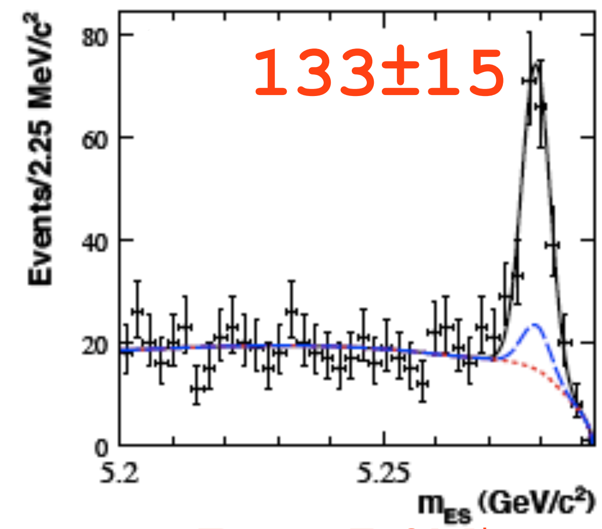
$B^\pm \rightarrow D^0K^\pm$



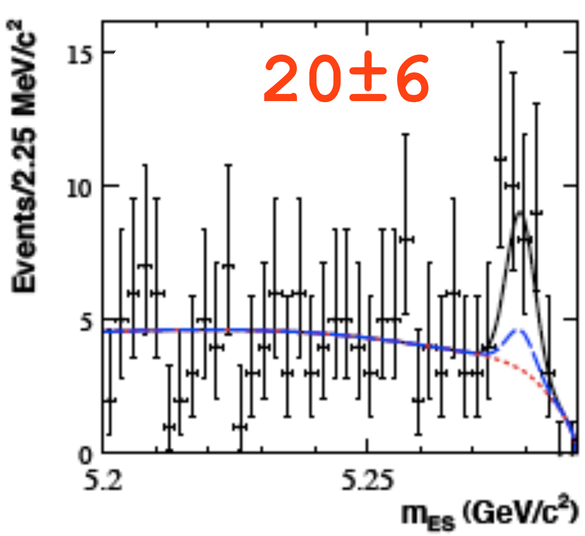
$B^\pm \rightarrow D^0K^\pm$



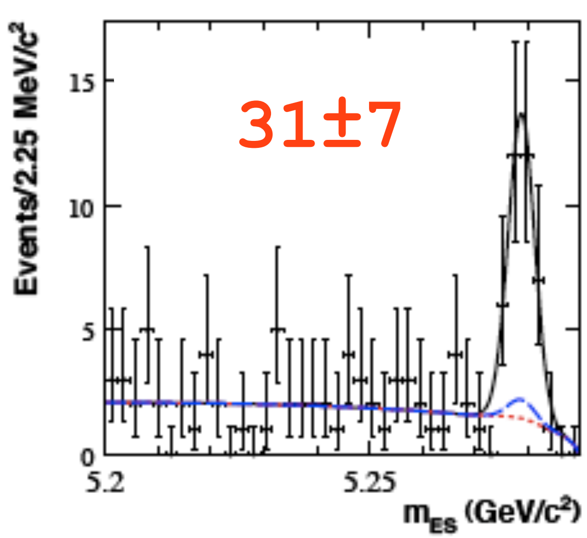
$B^\pm \rightarrow D^{*0}[D^0\pi^0]K^\pm$



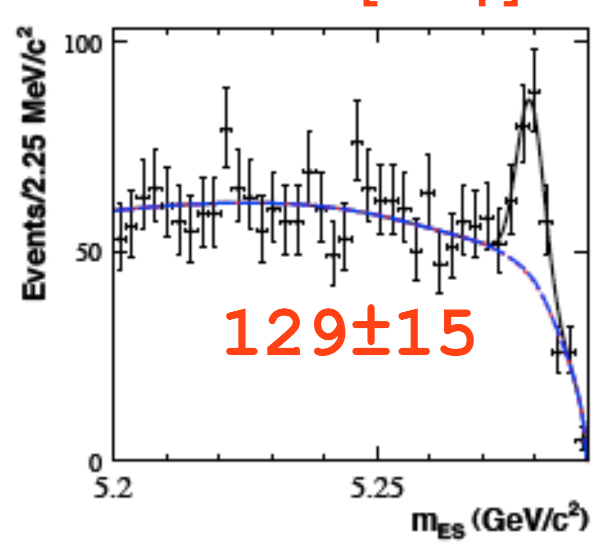
$B^\pm \rightarrow D^{*0}[D^0\gamma]K^\pm$



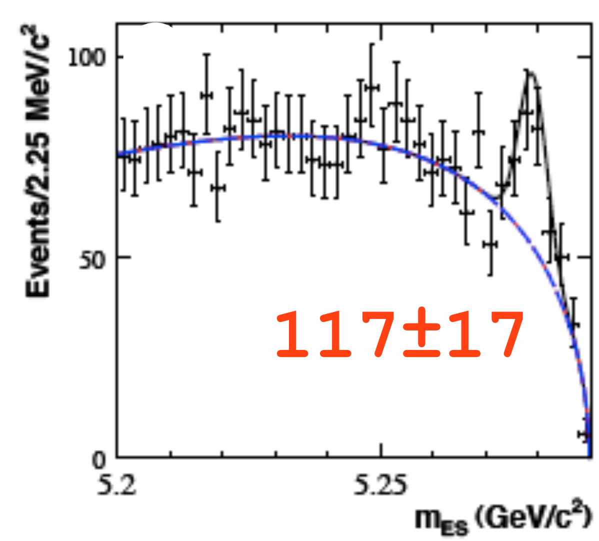
$B^\pm \rightarrow D^{*0}[D^0\pi^0]K^\pm$



$B^\pm \rightarrow D^{*0}[D^0\gamma]K^\pm$

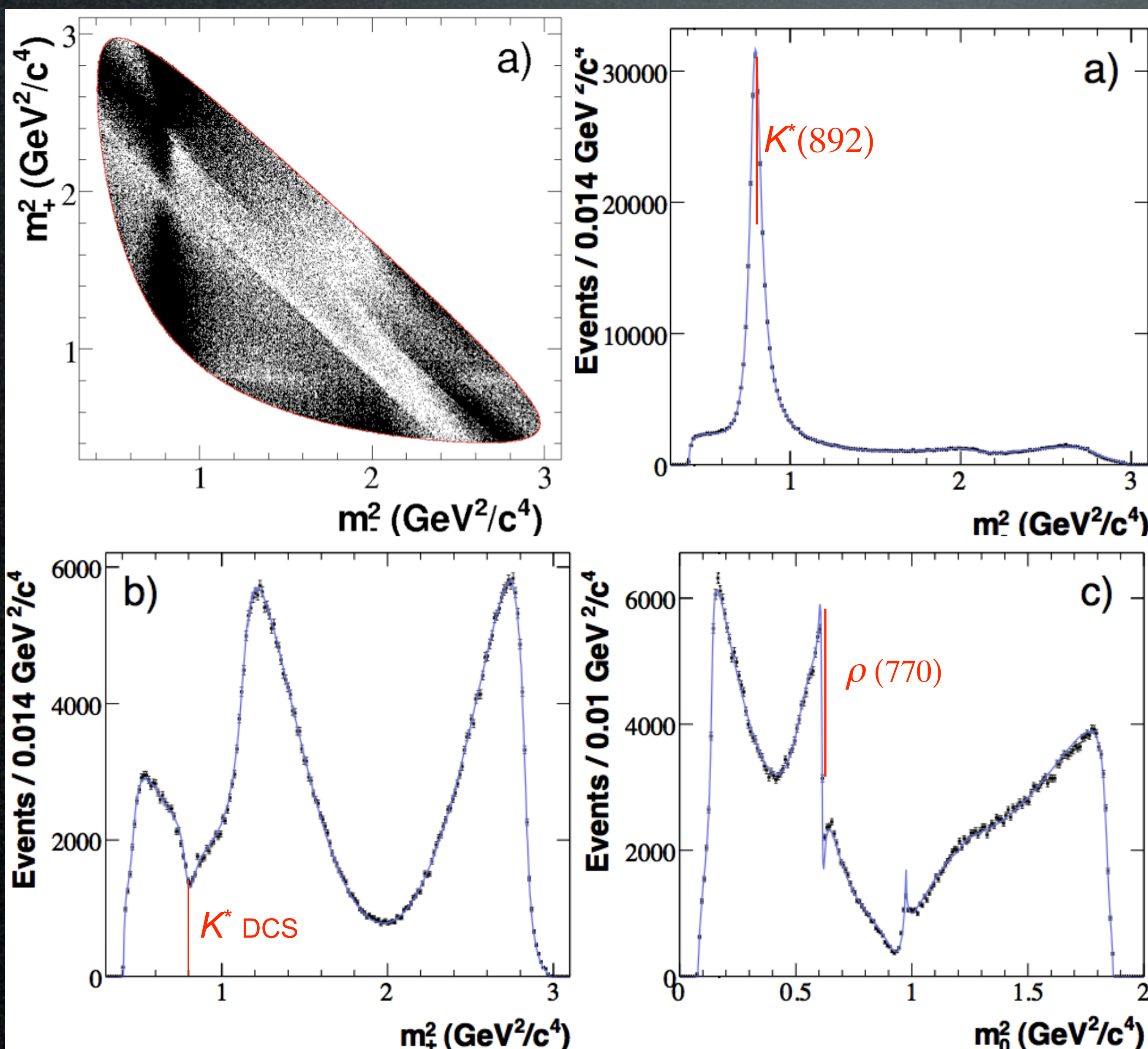


$B^\pm \rightarrow D^0K^{*\pm}$



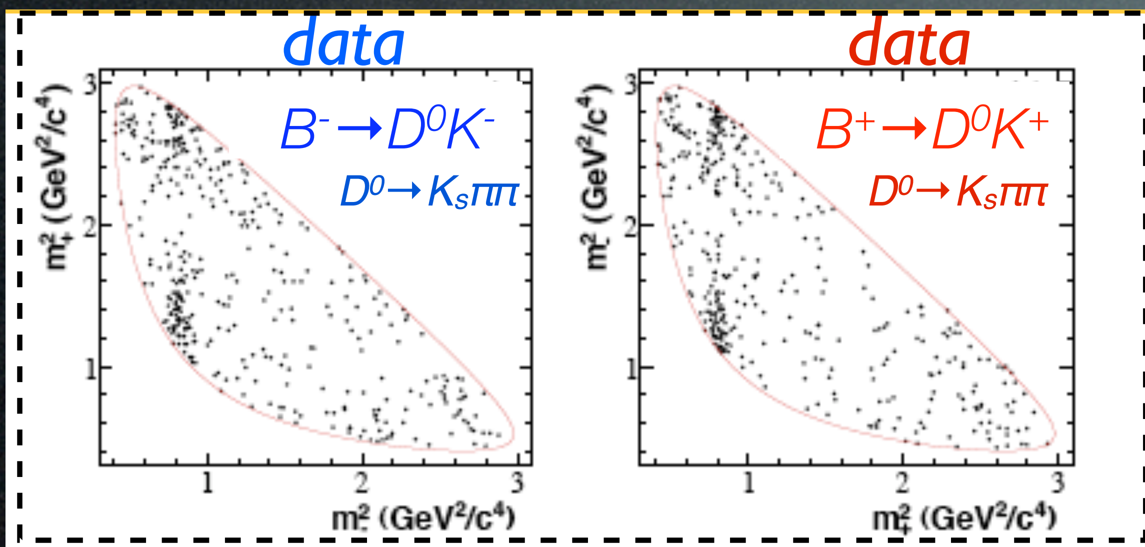
D^0 Dalitz models from D^* data

- Sample of 487K D0->Kspipi events, flavor tagged from D*+-->D0pi+- selected with 98% purity
- Isobar model (sum of Breit-Wigner amplitudes, quasi two-body approximation)
- Resonance fractions estimated by fit to the data



Component	a_r	ϕ_r (deg)	Fraction (%)
$K^*(892)^-$	1.740 ± 0.010	139.0 ± 0.3	55.7 ± 2.8
$K_0^*(1430)^-$	8.2 ± 0.7	153 ± 8	10.2 ± 1.5
$K_2^*(1430)^-$	1.410 ± 0.022	138.4 ± 1.0	2.2 ± 1.6
$K^*(1680)^-$	1.46 ± 0.10	-174 ± 4	0.7 ± 1.9
$K^*(892)^+$	0.158 ± 0.003	-42.7 ± 1.2	0.46 ± 0.23
$K_0^*(1430)^+$	0.32 ± 0.06	143 ± 11	< 0.05
$K_2^*(1430)^+$	0.091 ± 0.016	85 ± 11	< 0.12
$\rho(770)^0$	1	0	21.0 ± 1.6
$\omega(782)$	0.0527 ± 0.0007	126.5 ± 0.9	0.9 ± 1.0
$f_2(1270)$	0.606 ± 0.026	157.4 ± 2.2	0.6 ± 0.7
β_1	9.3 ± 0.4	-78.7 ± 1.6	
β_2	10.89 ± 0.26	-159.1 ± 2.6	
β_3	24.2 ± 2.0	168 ± 4	
β_4	9.16 ± 0.24	90.5 ± 2.6	
$f_{11}^{\rm prod}$	7.94 ± 0.26	73.9 ± 1.1	
$f_{12}^{'\rm prod}$	2.0 ± 0.3	-18 ± 9	
$f_{13}^{'\rm prod}$	5.1 ± 0.3	33 ± 3	
$f_{14}^{'\rm prod}$	3.23 ± 0.18	4.8 ± 2.5	
$s_0^{\rm prod}$	-0.07 ± 0.03		
$\pi\pi$ S-wave			11.9 ± 2.6
M (GeV/c^2)	1.463 ± 0.002		
Γ (GeV/c^2)	0.233 ± 0.005		
F	0.80 ± 0.09		
ϕ_F	2.33 ± 0.13		
R	1		
ϕ_R	-5.31 ± 0.04		
a	1.07 ± 0.11		
r	-1.8 ± 0.3		

Dalitz plot method results



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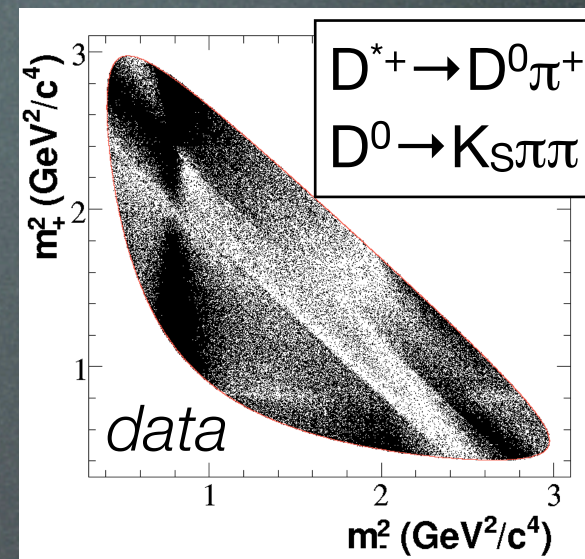

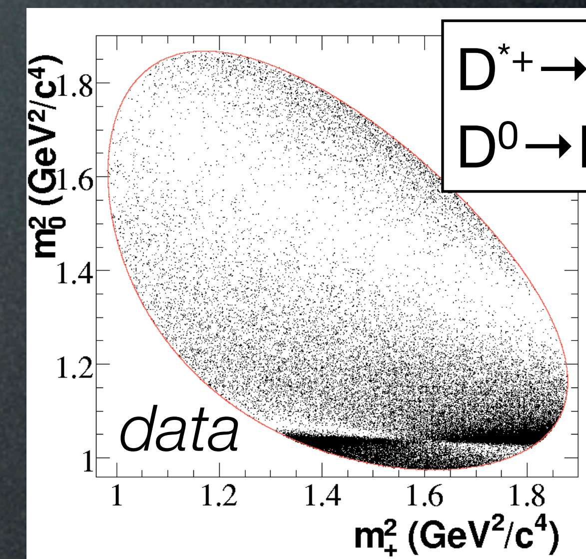

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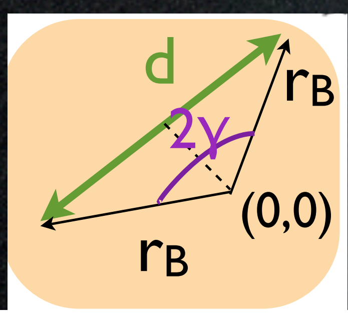
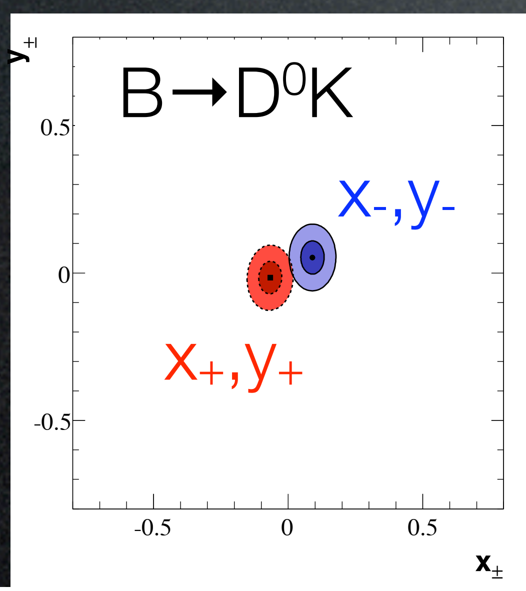
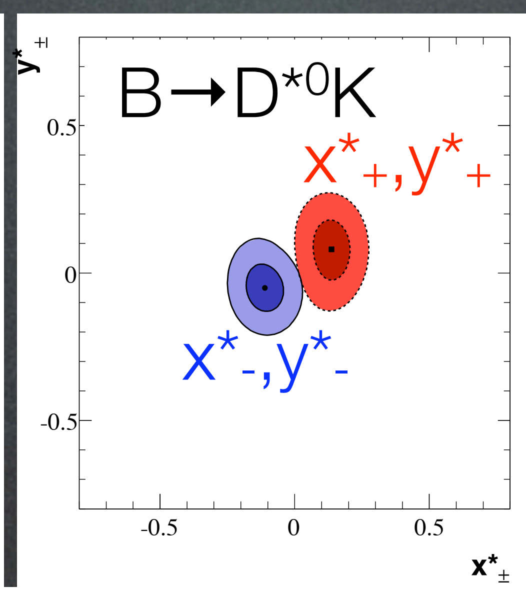
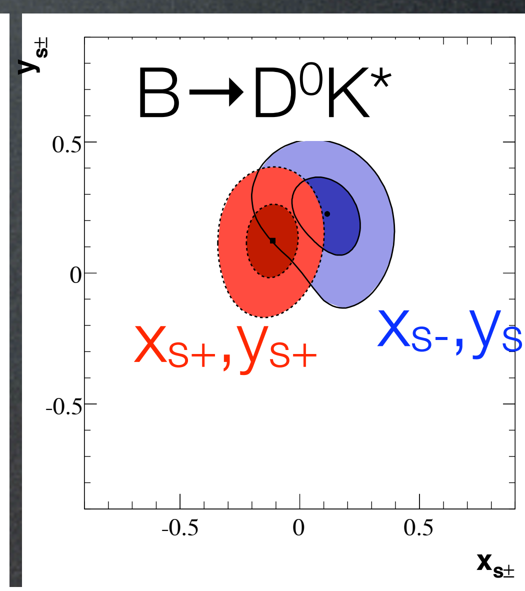


$d=2r_B|\sin\gamma|\neq 0 \Rightarrow$

direct CPV







CPV significance:

B→DK: 2.2σ

B→D*K: 2.5σ

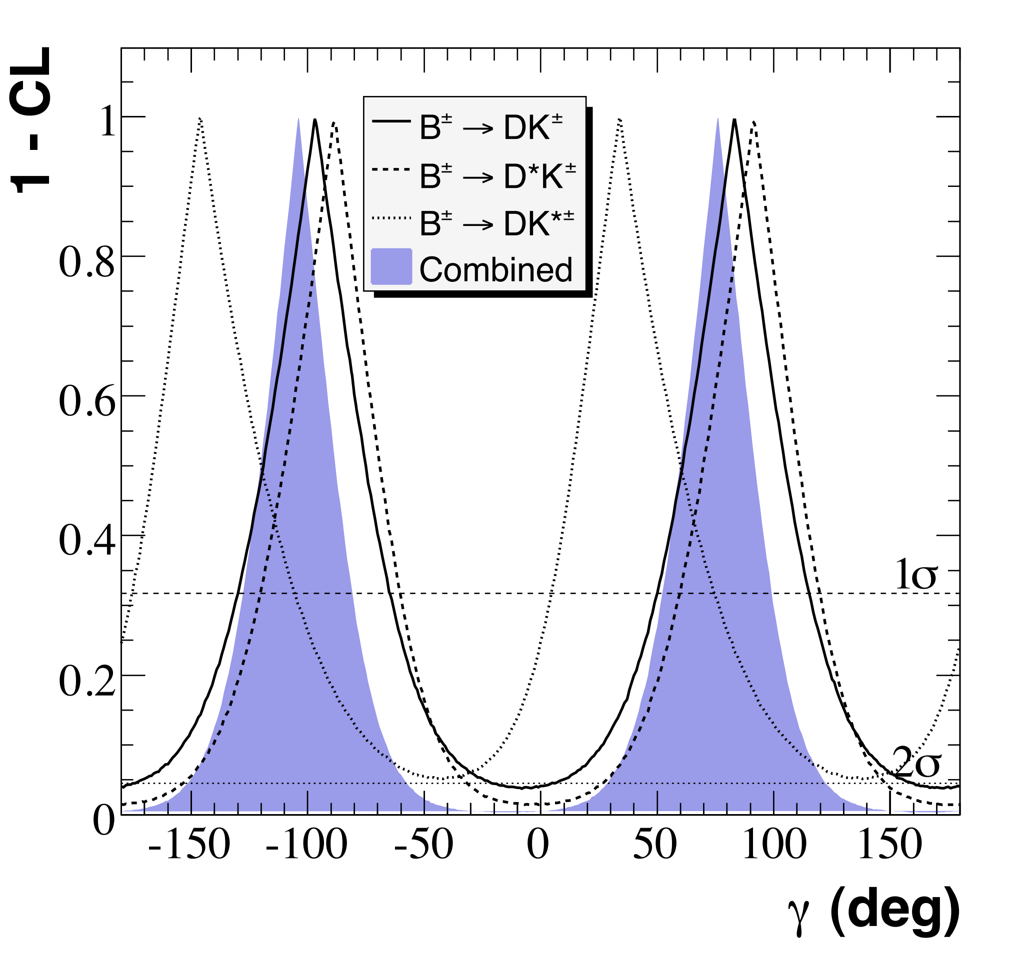
B→DK*: 1.5σ

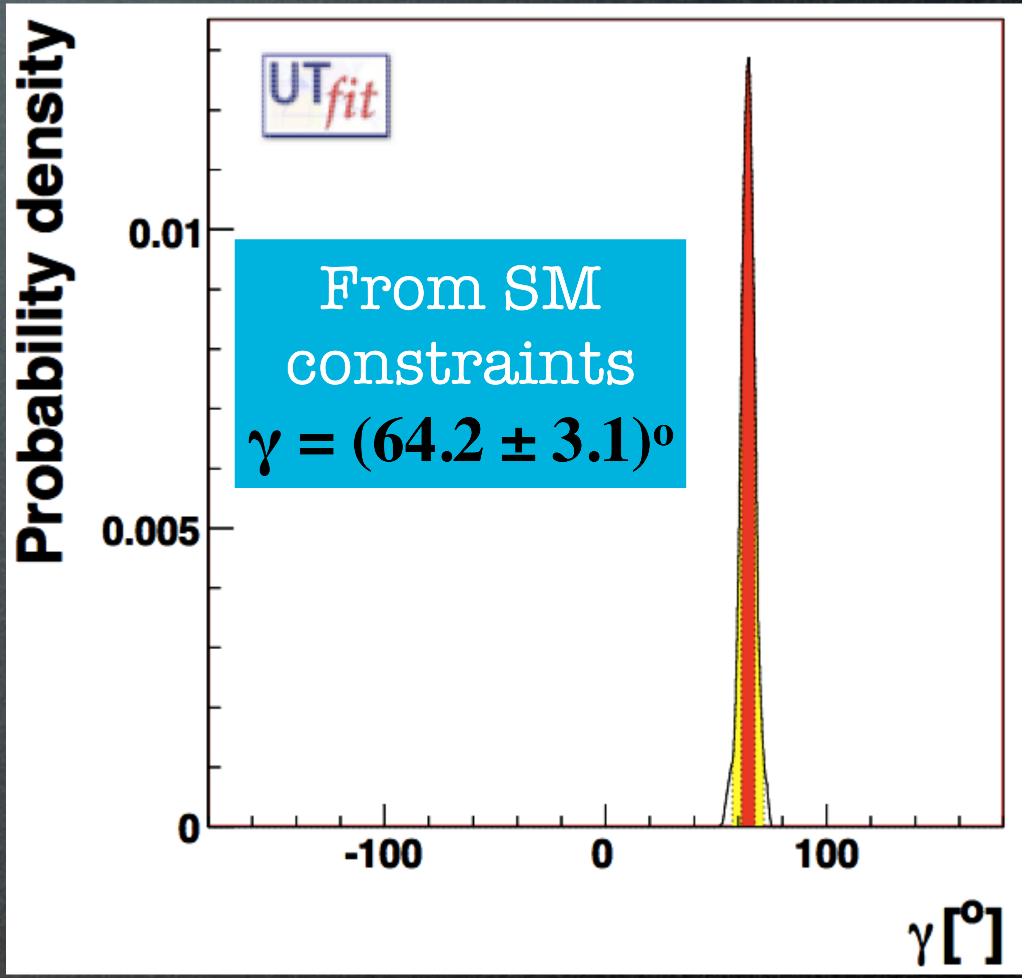
combined: 3.0σ

Parameters	$B^- \to \tilde{D}^0 K^-$	$B^- \to \tilde{D}^{*0} K^-$	$B^- \to \tilde{D}^0 K^{*-}$
x_- , x^*_- , x_{s-}	$0.090 \pm 0.043 \pm 0.015 \pm 0.011$	$-0.111 \pm 0.069 \pm 0.014 \pm 0.004$	$0.115 \pm 0.138 \pm 0.039 \pm 0.014$
y_- , y^*_- , y_{s-}	$0.053 \pm 0.056 \pm 0.007 \pm 0.015$	$-0.051 \pm 0.080 \pm 0.009 \pm 0.010$	$0.226 \pm 0.142 \pm 0.058 \pm 0.011$
x_+ , x^*_+ , x_{s+}	$-0.067 \pm 0.043 \pm 0.014 \pm 0.011$	$0.137 \pm 0.068 \pm 0.014 \pm 0.005$	$-0.113 \pm 0.107 \pm 0.028 \pm 0.018$
y_+ , y^*_+ , y_{s+}	$-0.015 \pm 0.055 \pm 0.006 \pm 0.008$	$0.080 \pm 0.102 \pm 0.010 \pm 0.012$	$0.125 \pm 0.139 \pm 0.051 \pm 0.010$

Dalitz-plot method results

- Use a frequentist method to obtain the physical parameters γ, r_B, δ_B from $(x_\pm, y_\pm)$





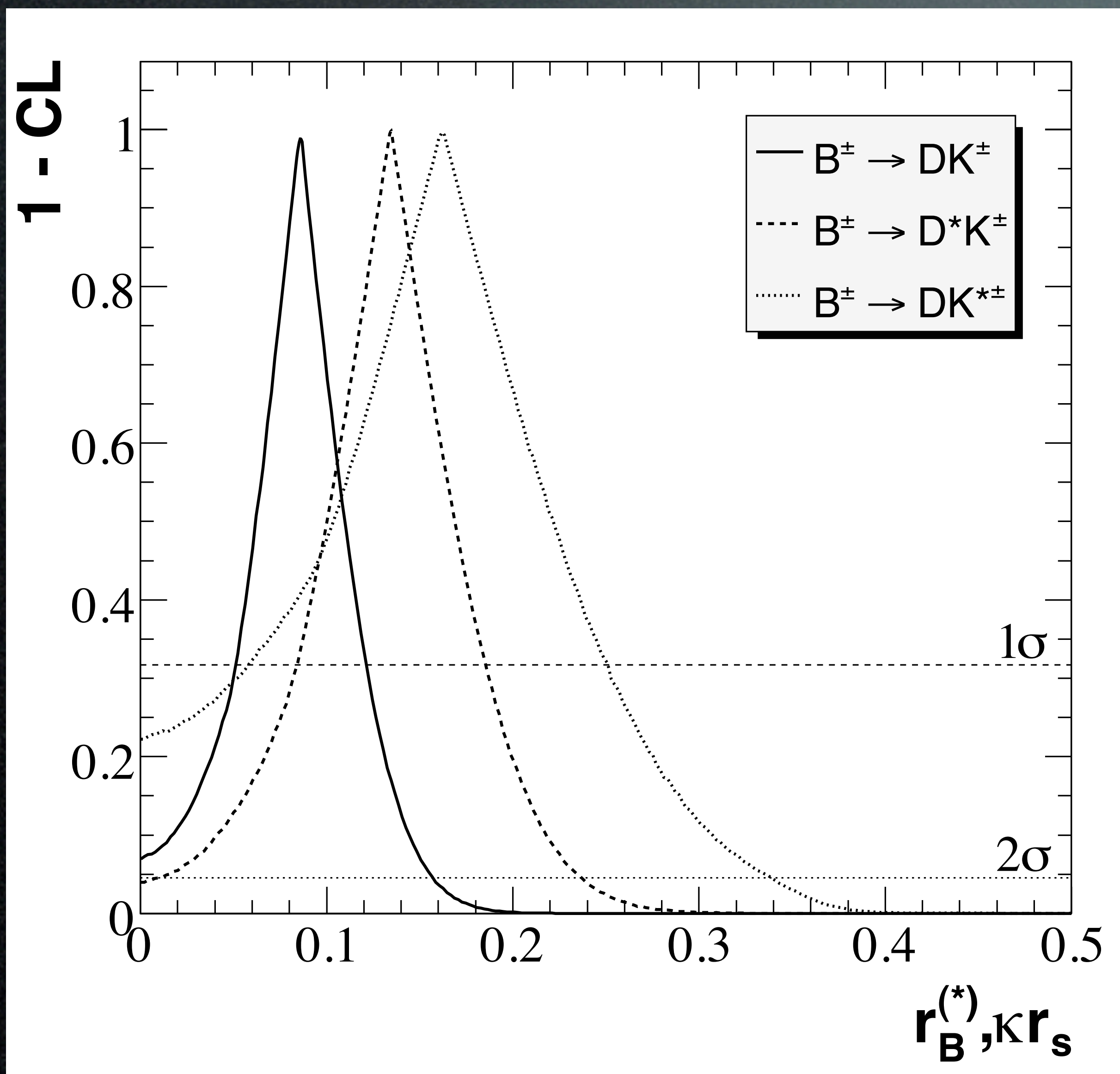
$$\gamma \ (\mathrm{mod}\ 180^\circ) = (76^{+23}_{-24})^\circ \{5^\circ, 5^\circ\}$$

total syst model

- Two-fold ambiguity
- Statistically-limited measurement

Dalitz-plot method results

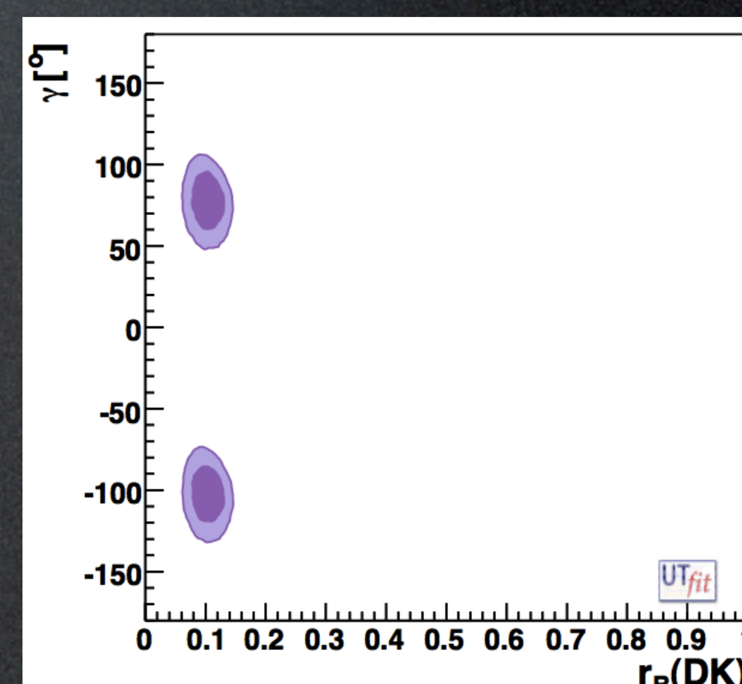
- Use a frequentist method to obtain the physical parameters γ, r_B, δ_B from $(x_\pm, y_\pm)$



$$\begin{array}{rclll} r_B & = & 0.086 \pm 0.035 & \{0.010, 0.011\} \\ r_B^* & = & 0.135 \pm 0.051 & \{0.011, 0.005\} \\ kr_s & = & 0.163^{+0.088}_{-0.105} & \{0.037, 0.021\} \end{array}$$

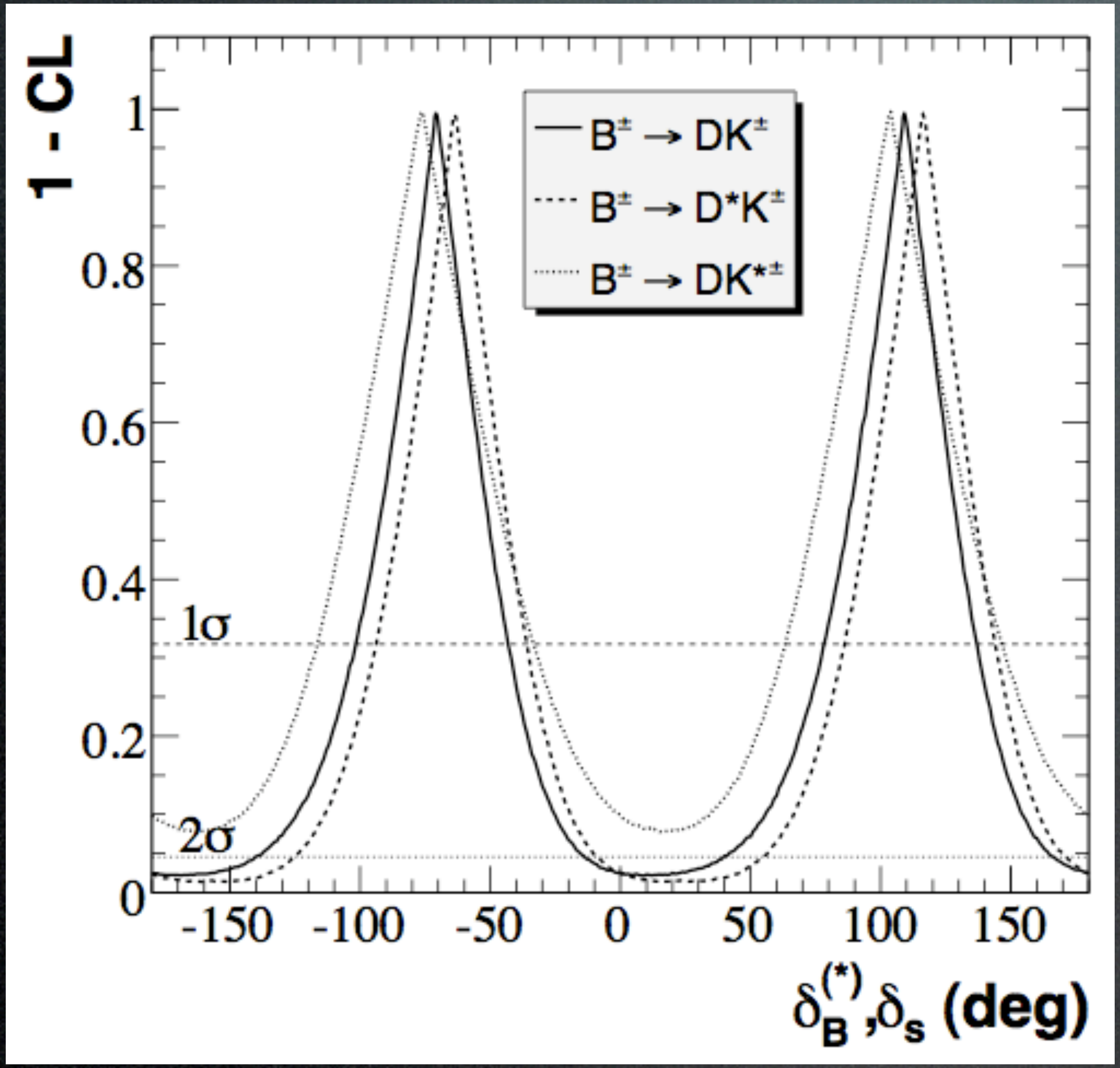
total syst model

- Small r_B (~0.1) is favored
  ⇒ limited sensitivity to γ



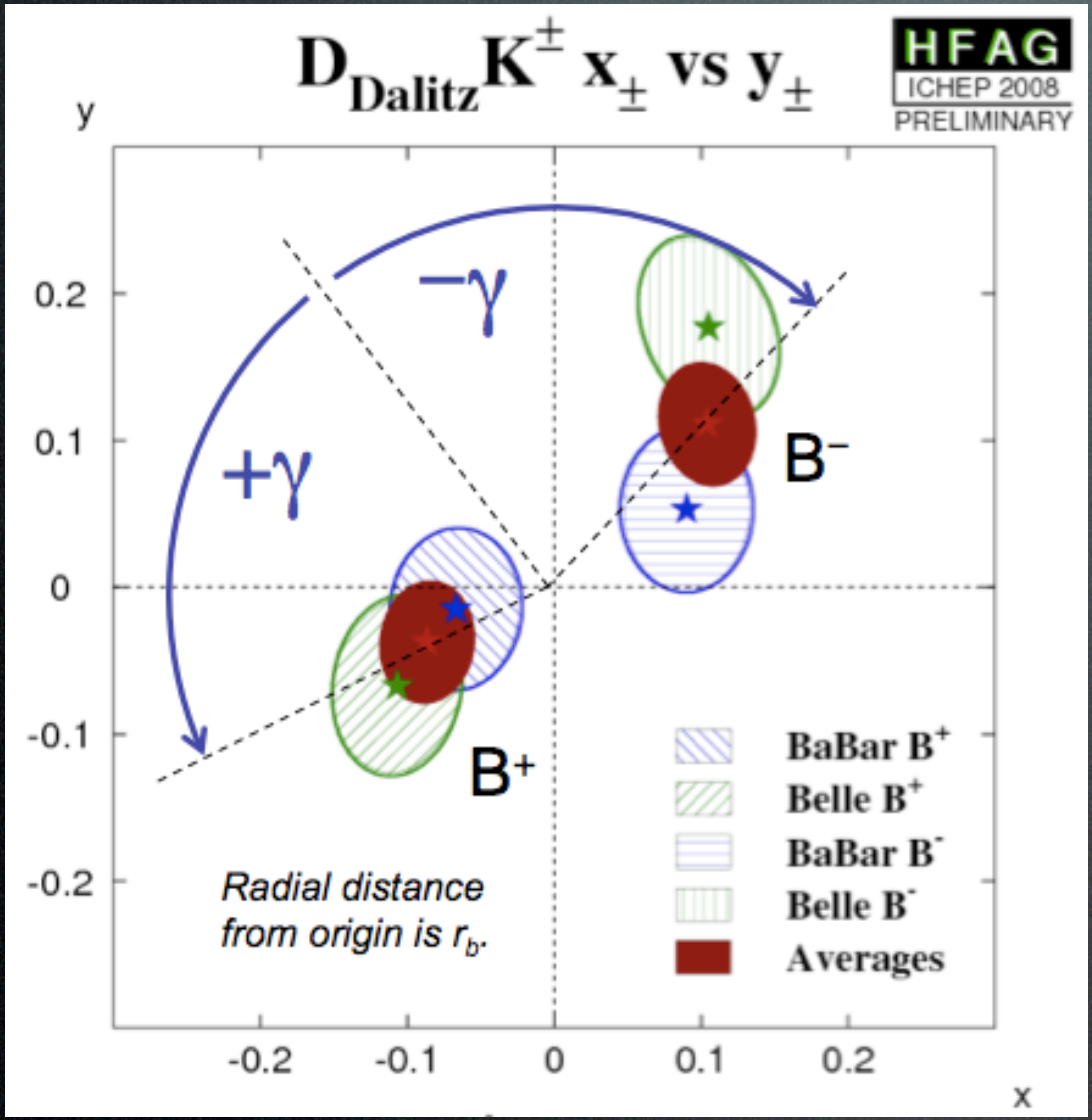
Dalitz-plot method results

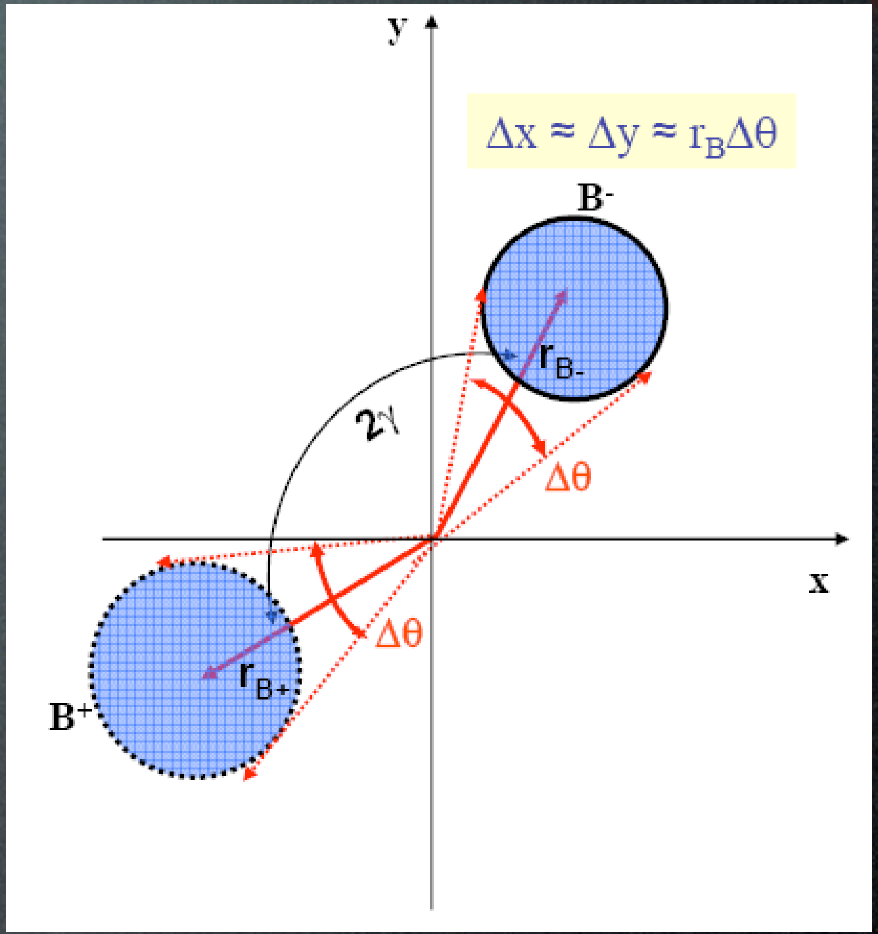
- Use a frequentist method to obtain the physical parameters γ, r_B, δ_B from $(x_\pm, y_\pm)$



- Two-fold ambiguity
- Significant strong phase in all three B decay modes

Comparison with Belle





	Babar	*Belle*
N_{BB}	383 M	657 M
N_{sig}	610 ± 34	533
γ^*	$(76 \pm 22 \pm 5 \pm 5)^o$	$(76\ ^{+12}_{-13} \pm 4 \pm 9)^o$
Ref.	PRD 78, 034023	arXiv:0803.3375

Note: errors on x± and y± are similar for BaBar and Belle.

* *Belle γ uses DK and D*K*
*BaBar γ uses DK, D*K, DK**

GLW method

GLW method

- Neutral D meson reconstructed in CP eigenstate final states (CP-even: K+K–, π+π- and CP-odd: $K_S\pi^0$, $K_S\omega$, $K_S\phi$) and in Cabibbo-favored Kπ final state

- Use measured $B^{\pm}$ yields to determine GLW-observables:

$$R_{CP\pm} = \frac{\Gamma(B^- \to D^0_{CP\pm}K^-) + \Gamma(B^+ \to D^0_{CP\pm}K^+)}{(\Gamma(B^- \to D^0 K^-) + \Gamma(B^+ \to \overline{D}^0 K^+))/2} = 1 + r_B^2 \pm 2r_B \cos\gamma \cos\delta_B$$

$$A_{CP\pm} = \frac{\Gamma(B^- \to D^0_{CP\pm}K^-) - \Gamma(B^+ \to D^0_{CP\pm}K^+)}{\Gamma(B^- \to D^0_{CP\pm}K^-) + \Gamma(B^+ \to D^0_{CP\pm}K^+)} = \frac{\pm 2r_B \sin\gamma \sin\delta_B}{R_{CP\pm}}$$

4 observables (3 independent), 3 unknowns: r_B, δ_B, γ

- Note that this method also gives access to the same **r_B, δ_B** parameters

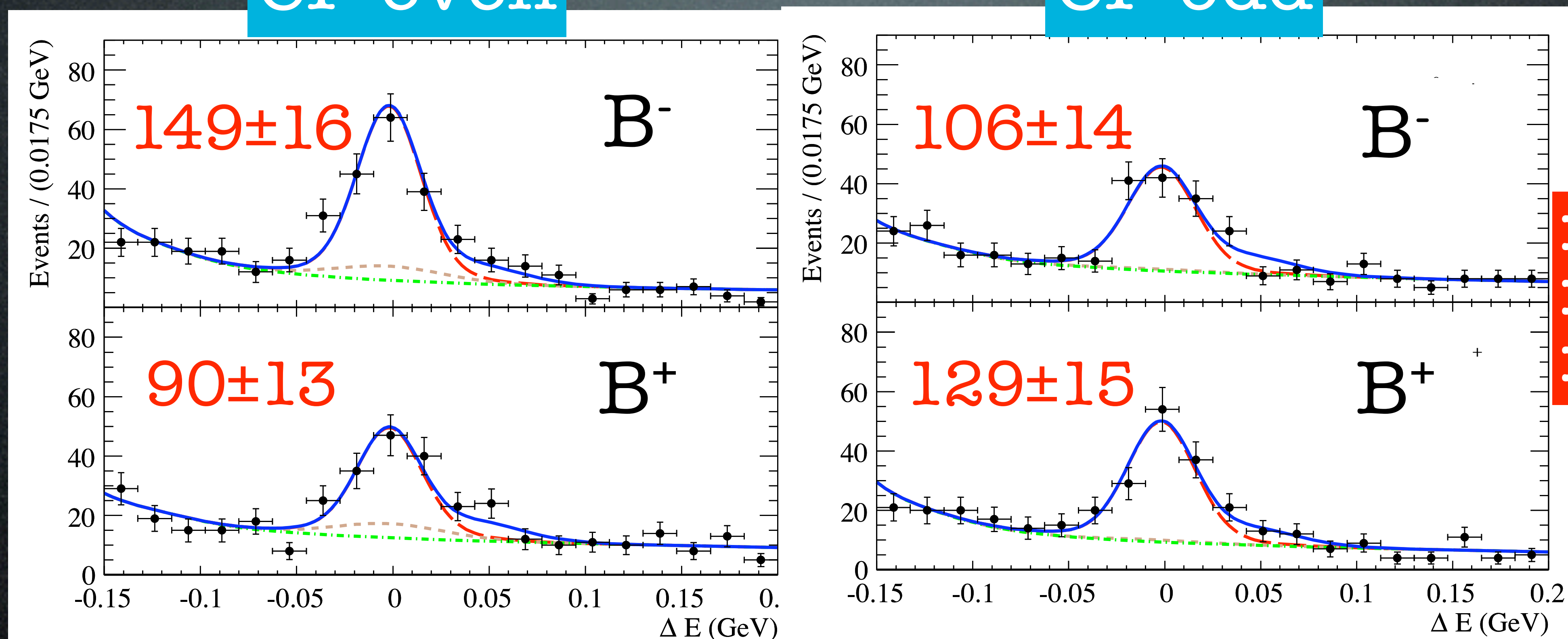
- Experimentally:
  - Selection based on m_{ES} and event shape variables
  - Extended maximum likelihood fit to the ΔE and Cherenkov angle of prompt track
  - Use $B \to D^{(*)0}\pi$ as normalization channel and control sample

$B^{\pm}\to D^0_{(CP)}K^{\pm}$ GLW results

CP-even

$N_{BB} = 383\times10^6$

CP-odd



$N_{CP+} = 239\pm21$
$N_{CP-} = 235\pm21$
$N_{K\pi} = 1872\pm51$

$$\begin{aligned} A_{CP+} &= \boxed{0.27 \pm 0.09 \pm 0.04} \\ A_{CP-} &= -0.09 \pm 0.09 \pm 0.02 \\ R_{CP+} &= 1.06 \pm 0.10 \pm 0.05 \\ R_{CP-} &= 1.03 \pm 0.10 \pm 0.05 \end{aligned}$$

$$x_{\pm} = \frac{R_{CP+}(1 \mp A_{CP+}) - R_{CP-}(1 \mp A_{CP-})}{4}$$

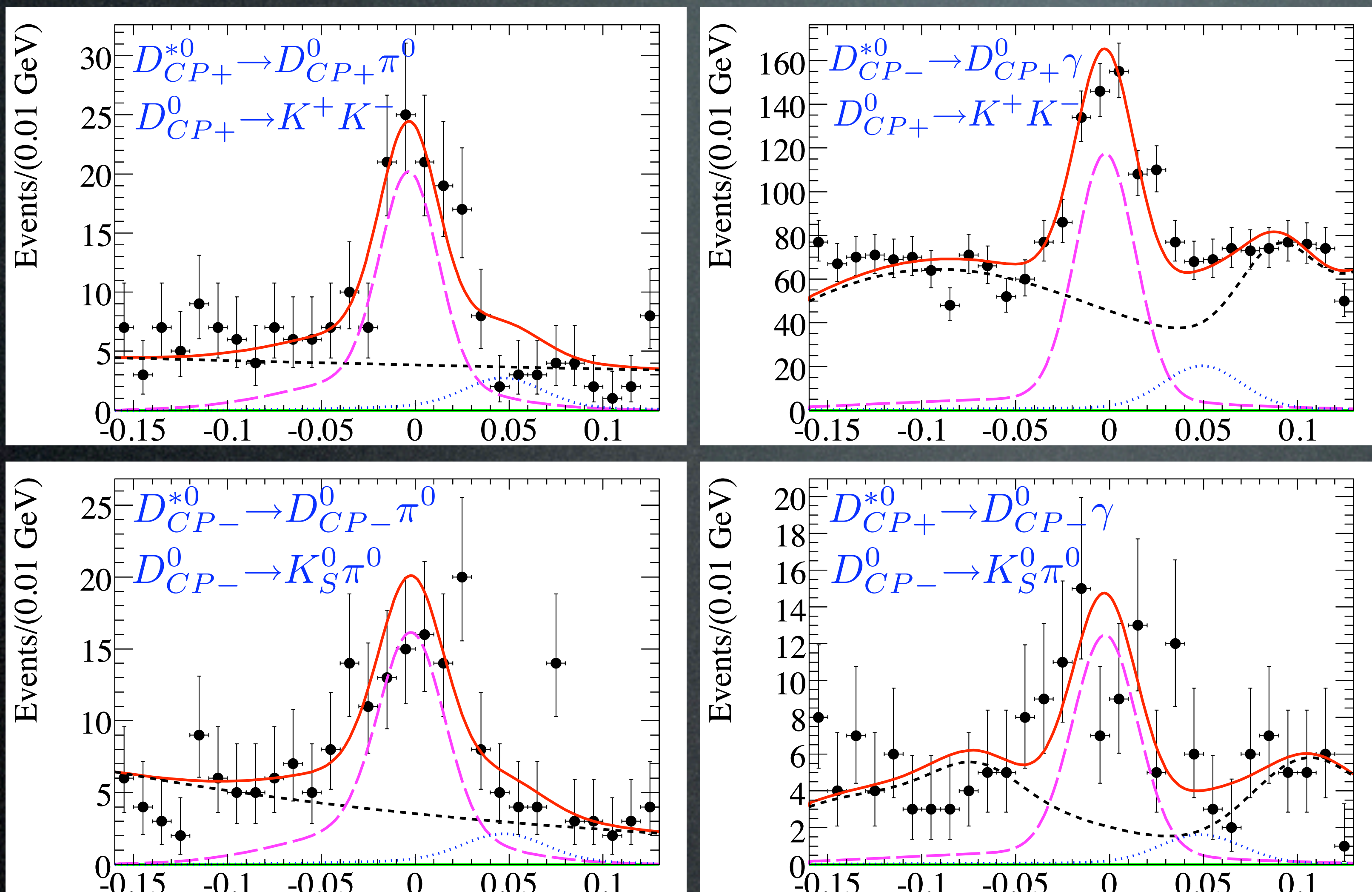
$$r^2 = x_{\pm}^2 + y_{\pm}^2 = \frac{R_{CP+} + R_{CP-} - 2}{2}$$

$$\begin{aligned} x_{+} &= -0.09 \pm 0.05 \pm 0.02 \\ x_{-} &= 0.10 \pm 0.05 \pm 0.03 \\ r_B^2 &= 0.05 \pm 0.07 \pm 0.03 \end{aligned}$$

- Direct CPV at 2.8σ in $B^{\pm}\to D^0_{CP+}K^{\pm}$ decays
- World's most precise measurement of $A_{CP\pm}$ and $R_{CP\pm}$
- Similar sensitivity to x and y as Dalitz analyses, helps constraints

$B^{\pm} \rightarrow D^{*0} K^{\pm}$ GLW results

$N_{BB} = 383 \times 10^6$



$N_{CP+} = 244 \pm 22$
$N_{CP-} = 225 \pm 23$
$N_{K\pi} = 1410 \pm 57$

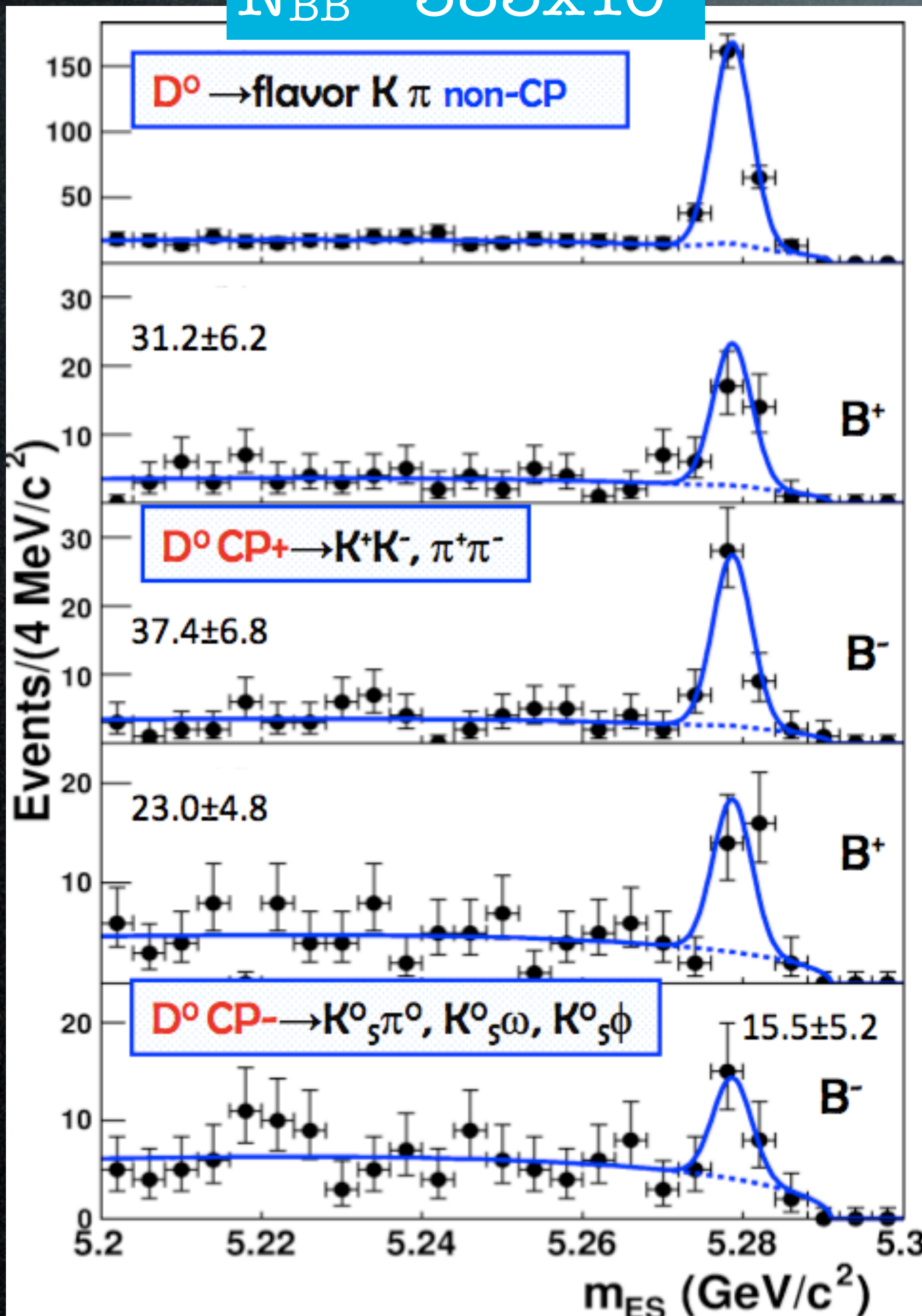
$$A^*_{CP+} = -0.11 \pm 0.09 \pm 0.01$$
$$A^*_{CP-} = 0.06 \pm 0.10 \pm 0.02$$
$$R^*_{CP+} = 1.31 \pm 0.13 \pm 0.04$$
$$R^*_{CP-} = 1.10 \pm 0.12 \pm 0.04$$

$$x^*_+ = 0.09 \pm 0.07 \pm 0.02$$
$$x^*_- = -0.02 \pm 0.06 \pm 0.02$$
$$r^{*\,2}_B = 0.22 \pm 0.09 \pm 0.03$$

- No hint of direct CPV
- World's most precise measurement of $A^*_{CP\pm}$ and $R^*_{CP\pm}$
- Similar sensitivity to x and y as Dalitz analyses, helps constraints

$B^{\pm}\rightarrow D^0K^{*\pm}$ GLW results

$N_{BB} = 383\mathrm{x}10^6$



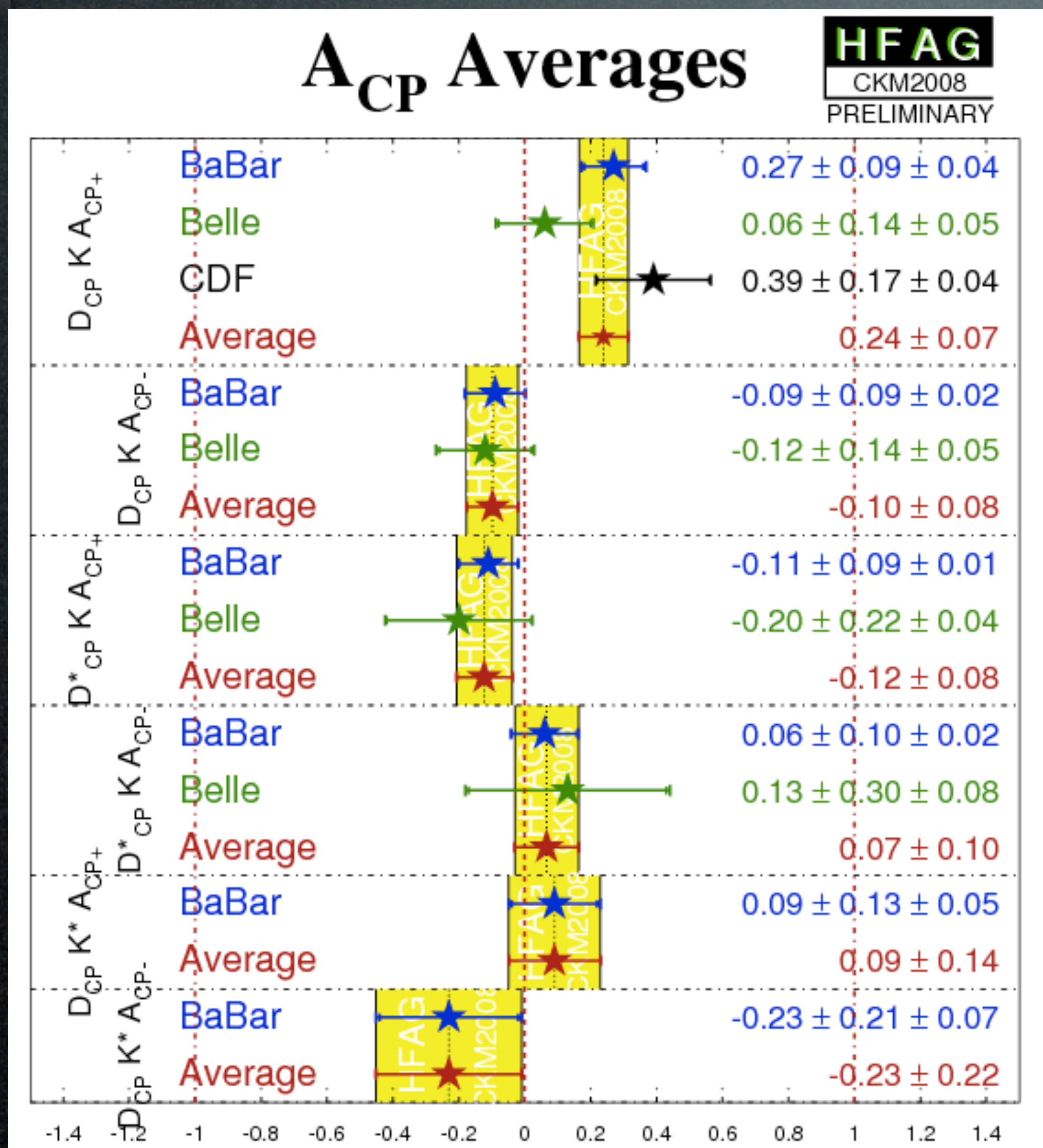
$N_{CP+} = 68.6\pm9.2$
$N_{CP-} = 38.5\pm7.0$
$N_{K\pi} = 231\pm17$

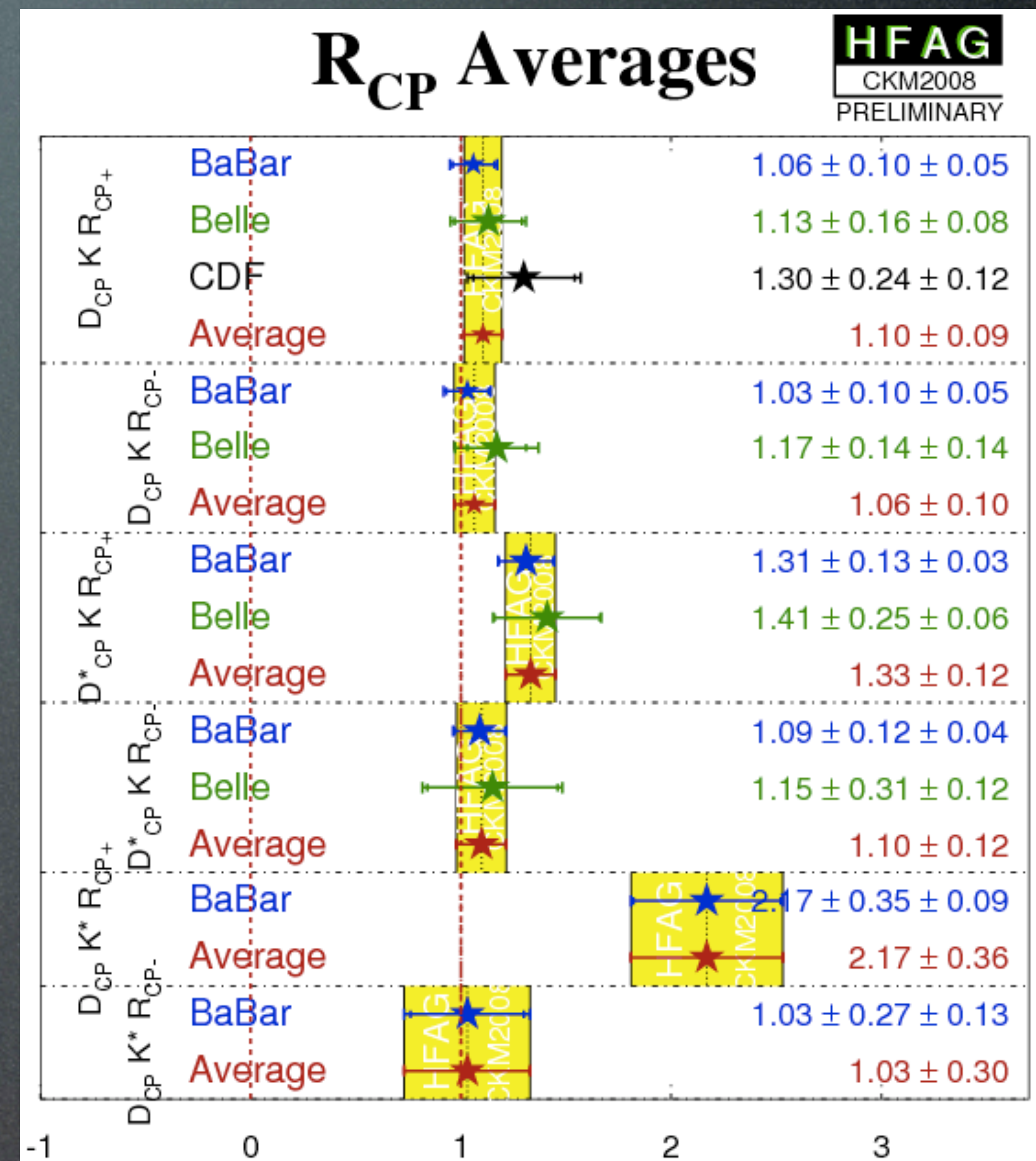
$$\begin{aligned}
A^s_{CP+} &= 0.09 \pm 0.13 \pm 0.05 \\
A^s_{CP-} &= -0.23 \pm 0.21 \pm 0.07 \\
R^s_{CP+} &= 2.17 \pm 0.35 \pm 0.09 \\
R^s_{CP-} &= 1.03 \pm 0.27 \pm 0.13
\end{aligned}$$

$$\begin{aligned}
x_{s+} &= 0.18 \pm 0.14 \pm 0.05 \\
x_{s-} &= 0.38 \pm 0.14 \pm 0.05
\end{aligned}$$

- Not sensitive enough to extract r_B
- Affected by low statistics at the moment, expect to become more significant with the rest of the dataset
- The only GLW measurement of this channel

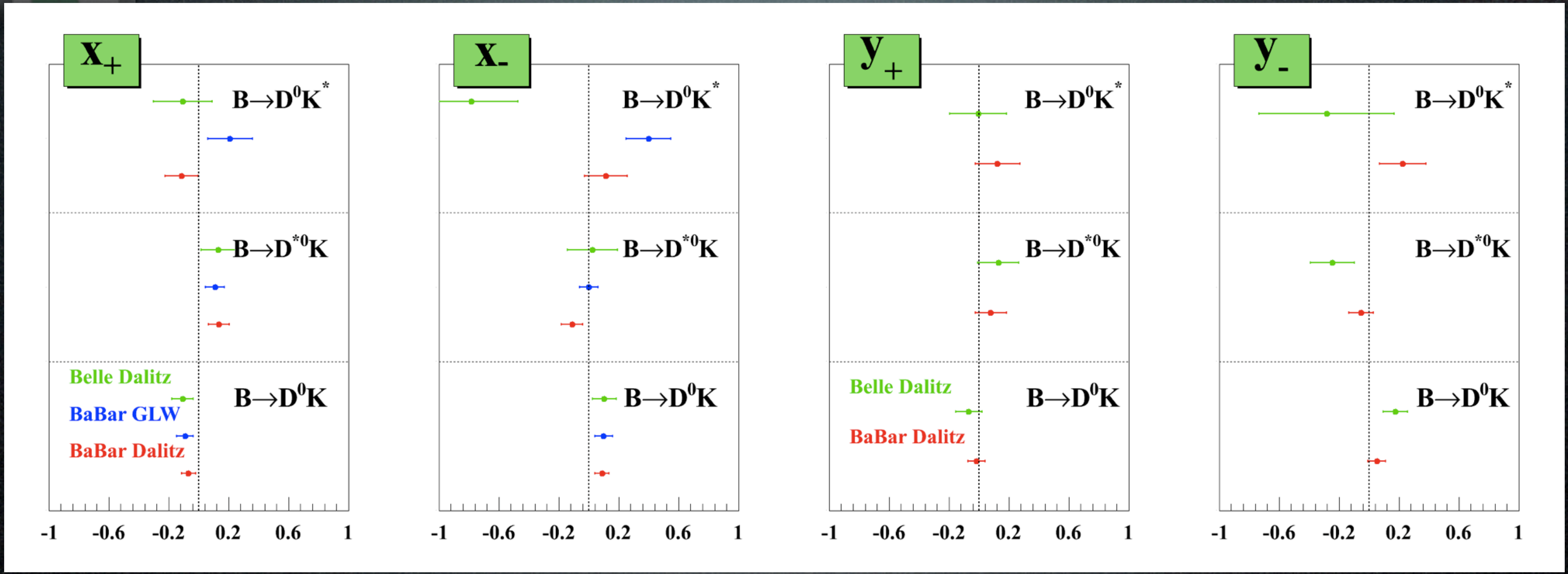
GLW A_{CP} and R_{CP} comparison





- Consistency with other experiments' determinations
- World's most precise measurement of $A_{CP\pm}$ and $R_{CP\pm}$

x and y GLW



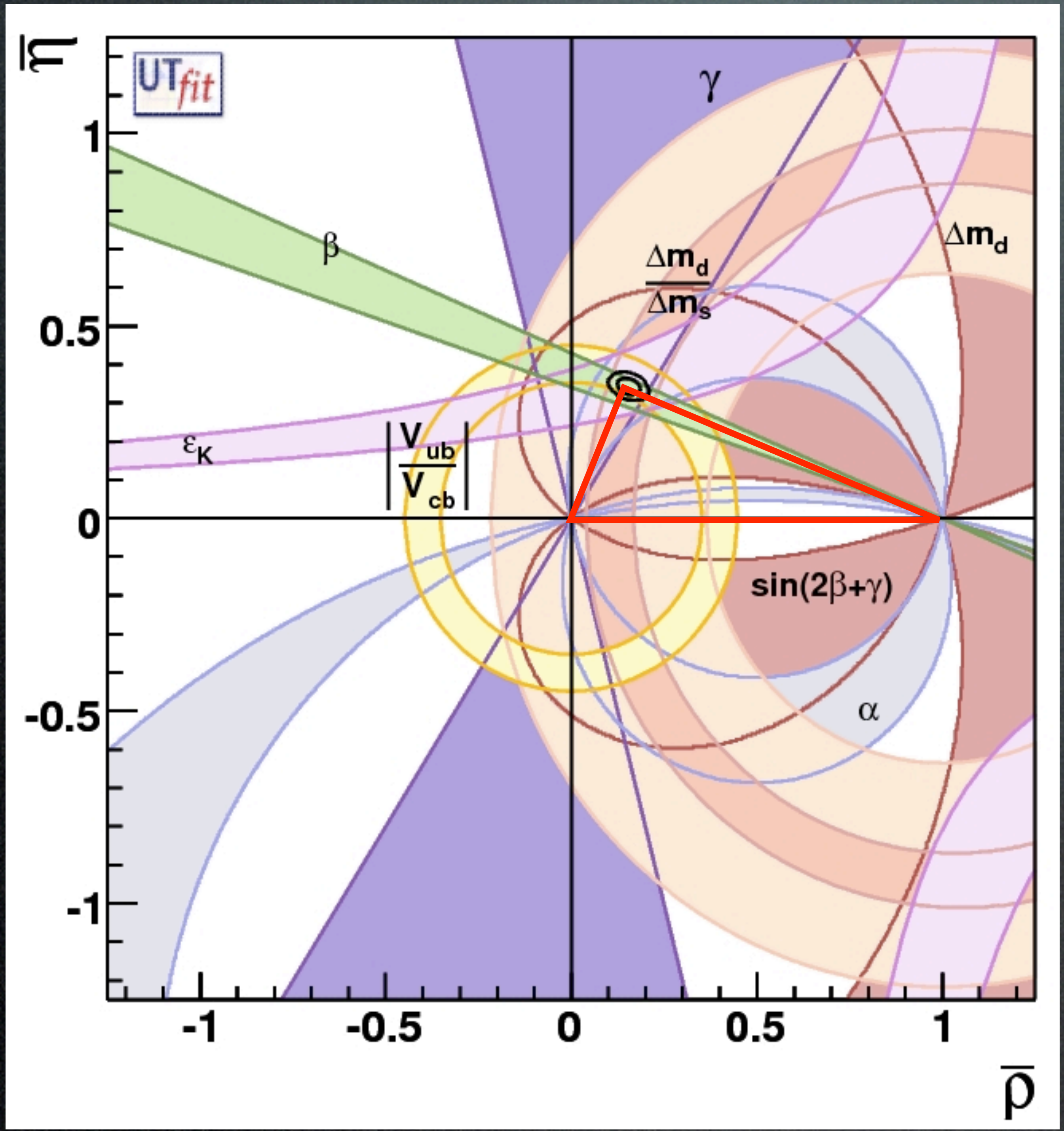
$x^{(*)}=r_B^{(*)}\cos(\delta_B^{(*)}\pm\gamma)$ $y^{(*)}=r_B^{(*)}\sin(\delta_B^{(*)}\pm\gamma)$

x,y depend on B decay due to different r,δ

- Similar precision on $x_\pm,y_\pm$ between BaBar and Belle Dalitz measurements
- Similar precision on $x_\pm$ between BaBar Dalitz and GLW analyses
- GLW results consistent with Dalitz ones and with SM expectations
- Expect a few degrees reduction in σ_γ when properly combined

Constraining the Unitary Triangle

- A look at the combined picture of all experimental information constraining the Unitarity Triangle:



	Direct Measurement		SM Fit not including Measurement
$\beta \approx$	1°	$\approx$	1.5°
$\alpha \approx$	4°	$\approx$	5°
$\gamma \approx$	25°	$\approx$	5°

Future of γ measurements

- All the results for the B factories need to be updated with full dataset
- Expect improvement of the order of 20% once all channels are combined
- New model independent Dalitz results will become available
- Immediate future will be at LHCb, predicted sensitivity from MoriondEW09:

LHCb-2008-031

Tree Level Processes

Combination:

$B^{\pm} \to D^0 K^{\pm}$

$B^0 \to D^0 K^{*0}$

Time dependent:

$B^0 \to D\pi \quad B_s \to D_s K$

δ_{B^0} (°)	0	45	90	135	180
σ_γ for 0.5 fb^{-1} (°)	8.1	10.1	9.3	9.5	7.8
σ_γ for 2 fb^{-1} (°)	4.1	5.1	4.8	5.1	3.9
σ_γ for 10 fb^{-1} (°)	2.0	2.7	2.4	2.6	1.9

2° …3° reachable after 5 yr

- Of course SuperB factories would push the current analyses to essentially systematic uncertainties

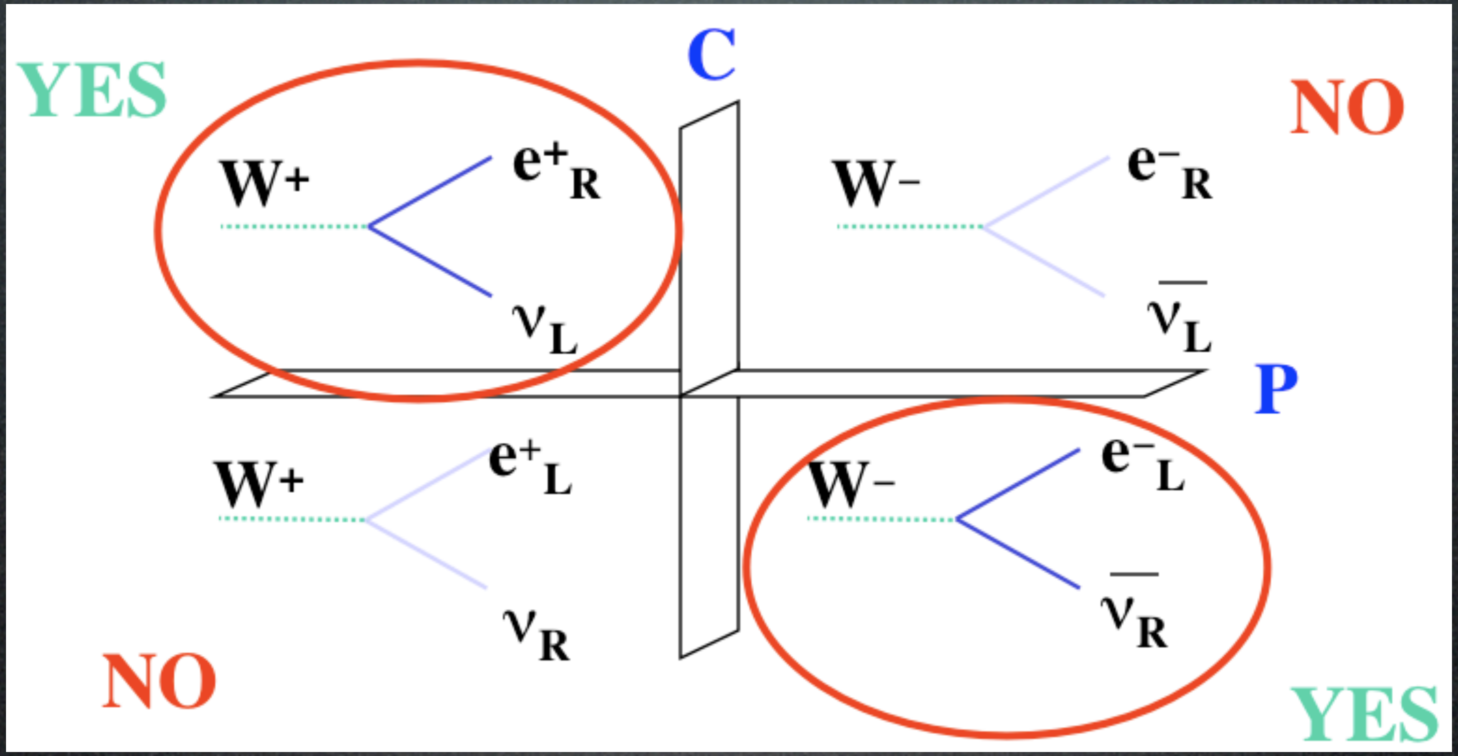
Conclusions

- Measurement of gamma is challenging
- Very active field: many new results published recently
- $\langle\gamma\rangle$ ~72°, dominated by Dalitz analysis, consistent with SM CKM fits
- Evidence of direct CP violation at the 3 sigma level
- Precision on γ approaching <20° region
  - NOT an original goal of BaBar's physics plan
  - achieved with much effort by combining several methods and B decays
  - limited by available statistics
  - still improvement from remaining BaBar data available and latest data reprocessing
- Interference effects (r) confirmed to be small (0.1-0.3)
  - very high statistics (≈100x) needed to reach σ_γ=1°
- Interesting future at LHCb and SuperB

Back-up

Weak Interactions violations

- In 1956, Lee and Yang proposed, and in 1957, Wu and others showed experimentally, that nature is not invariant under PARITY transformation.
- In the Standard Model, C and P are maximally violated in charged weak interactions



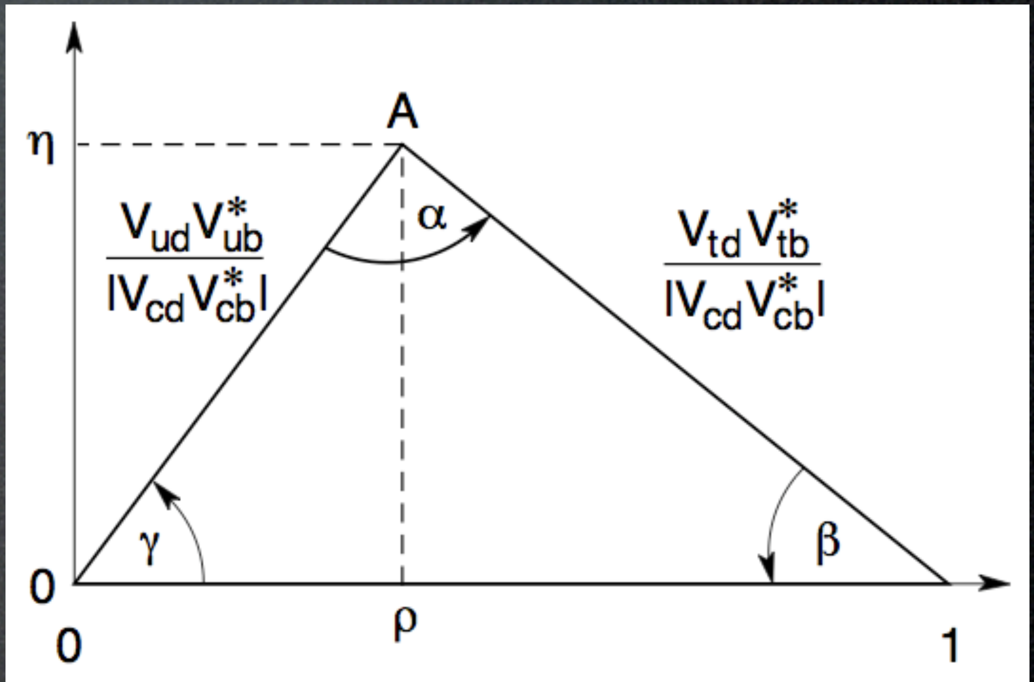
- But CP appears to be OK.

CKM in Wolfenstein convention

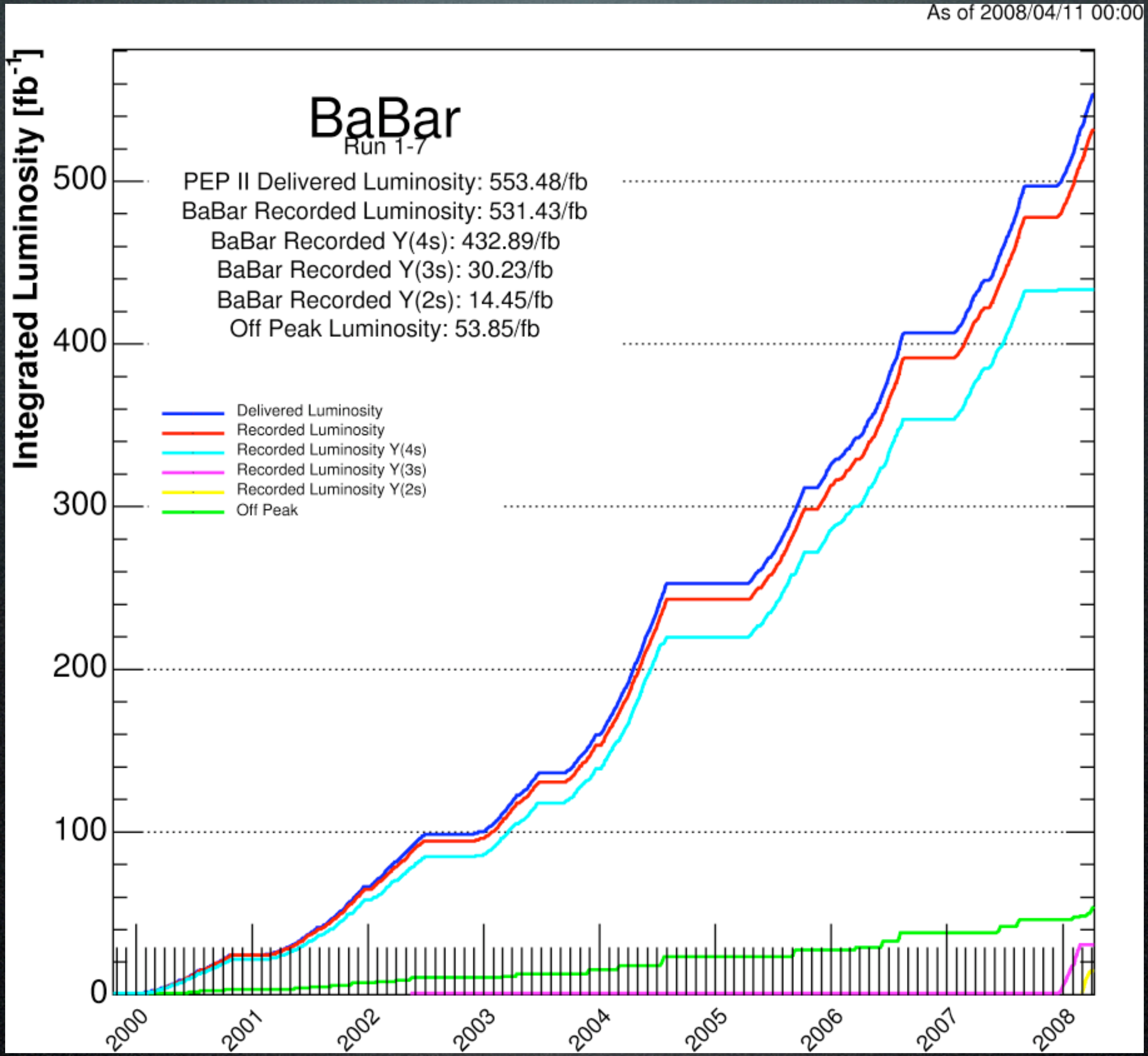
- Quark mixing can be described in terms of a matrix V which can be expressed (in the Wolfenstein convention) in terms of 4 parameters:

$$\mathbf{V} = \begin{vmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{vmatrix} = \begin{vmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{vmatrix} + O(\lambda^4)$$

- CP Violation arises from the presence of phase factors in some of the elements, i.e. from a non-vanishing value of η in this convention.
- $A \simeq 0.8$, $\lambda \simeq 0.22$
- $V_{ub} = \sqrt{\bar{\rho}^2 + \bar{\eta}^2} e^{-i\gamma}$



PEP-II B-Factory performance



The BaBar Experiment

- Outstanding K ID
- Precision tracking (Δt measurement)
- High resolution calorimeter
- Data collection efficiency >95%

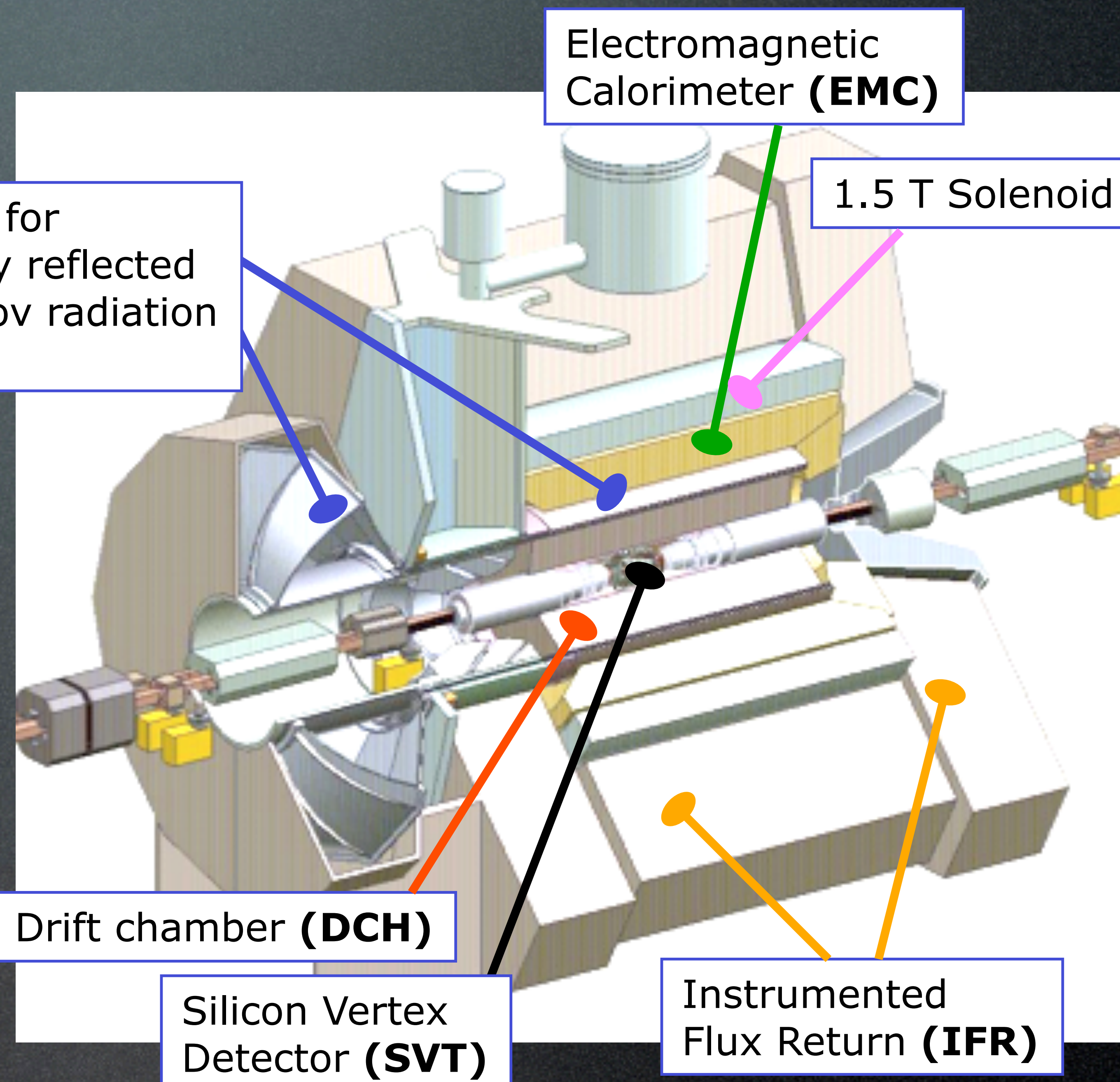
SVT: 5 layers double-sided Si.

DCH: 40 layers in 10 super-layers, axial and stereo.

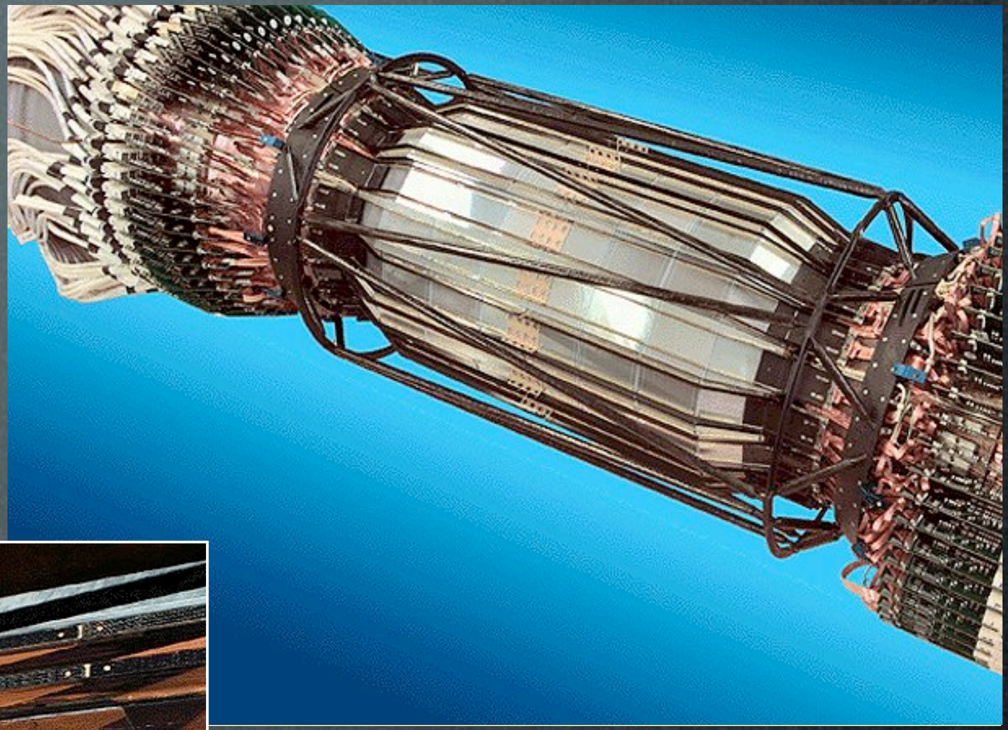
DIRC: Array of precisely machined quartz bars.

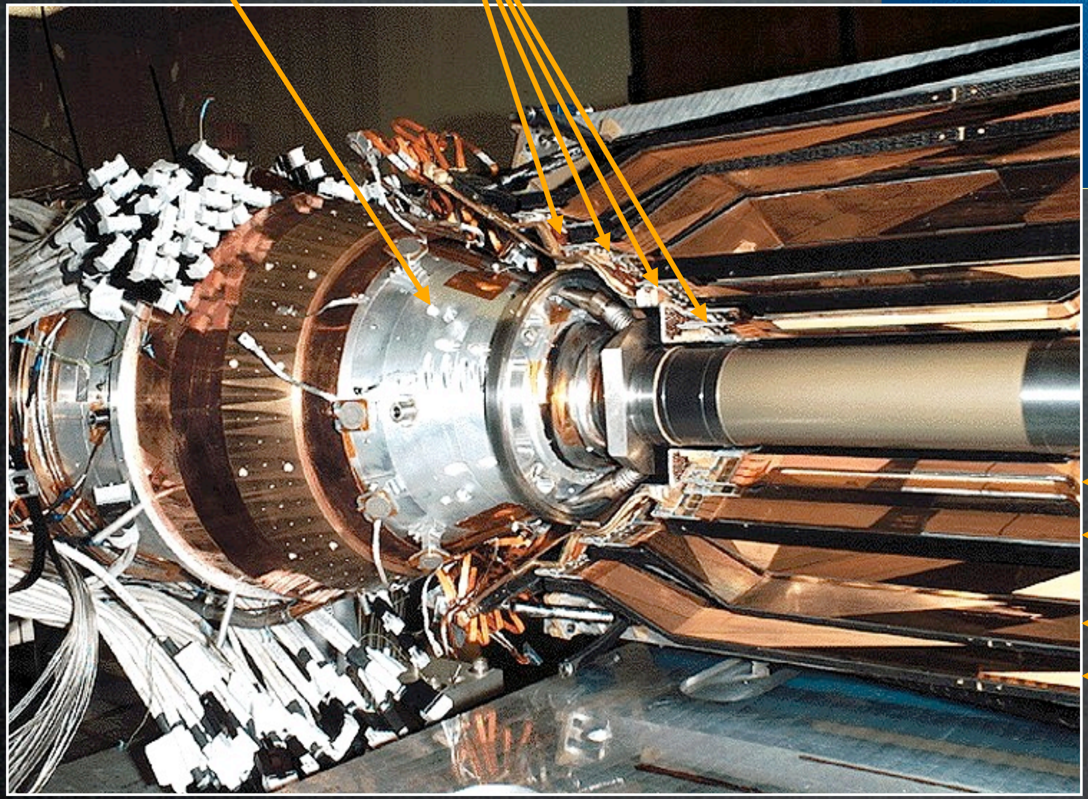
EMC: Crystal calorimeter (CsI(Tl)) Very good energy resolution. Electron ID, π^0 and γ reco.

IFR: Layers of RPCs within iron. Muon and neutral hadron (K_L)



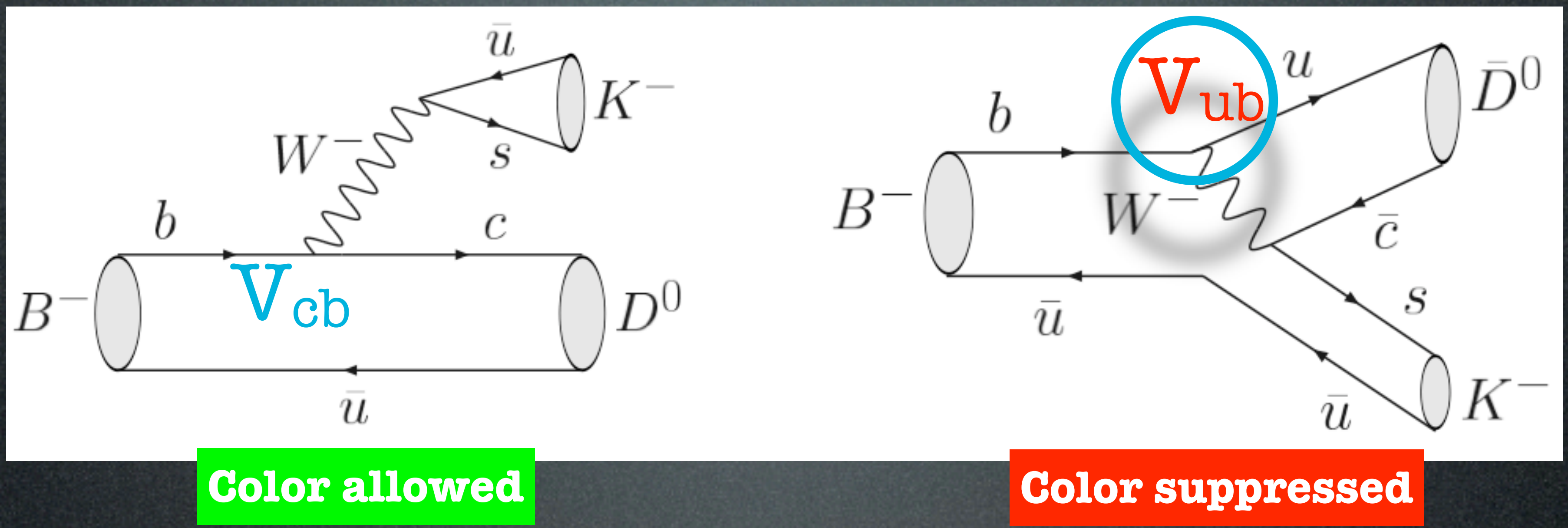
Silicon Vertex Detector





ADS method

- The idea is to use a final state where the two amplitude are comparable, use Double Cabibbo Suppressed D0->K+pi-:



(add box, wrong/right sign D decay)

- Expect large interference due to the suppressed vs favored D decay
- Challenge is the really small BF
- Two observables related to gamma

$$A_{ADS} \equiv \frac{\Gamma(B^- \to D[\to f]K^-) - \Gamma(B^+ \to D[\to \bar{f}]K^+)}{\Gamma(B^- \to D[\to f]K^-) + \Gamma(B^+ \to D[\to \bar{f}]K^+)} = 2 r_b r_D S \sin\gamma / R_{ADS}$$

$$R_{ADS} \equiv \frac{\Gamma(B^- \to D[\to f]K^-) + \Gamma(B^+ \to D[\to \bar{f}]K^+)}{\Gamma(B^- \to D[\to \bar{f}]K^-) + \Gamma(B^+ \to D[\to f]K^+)} = r_b^2 + r_D^2 + 2 r_b r_D C \cos\gamma$$

Dalitz general case ampl's/rates

- Amplitude of interference for B-,B+ and D and D* cases, notation could be confusing so presented it for B- only and D case in the seminar. Here're the full expressions:

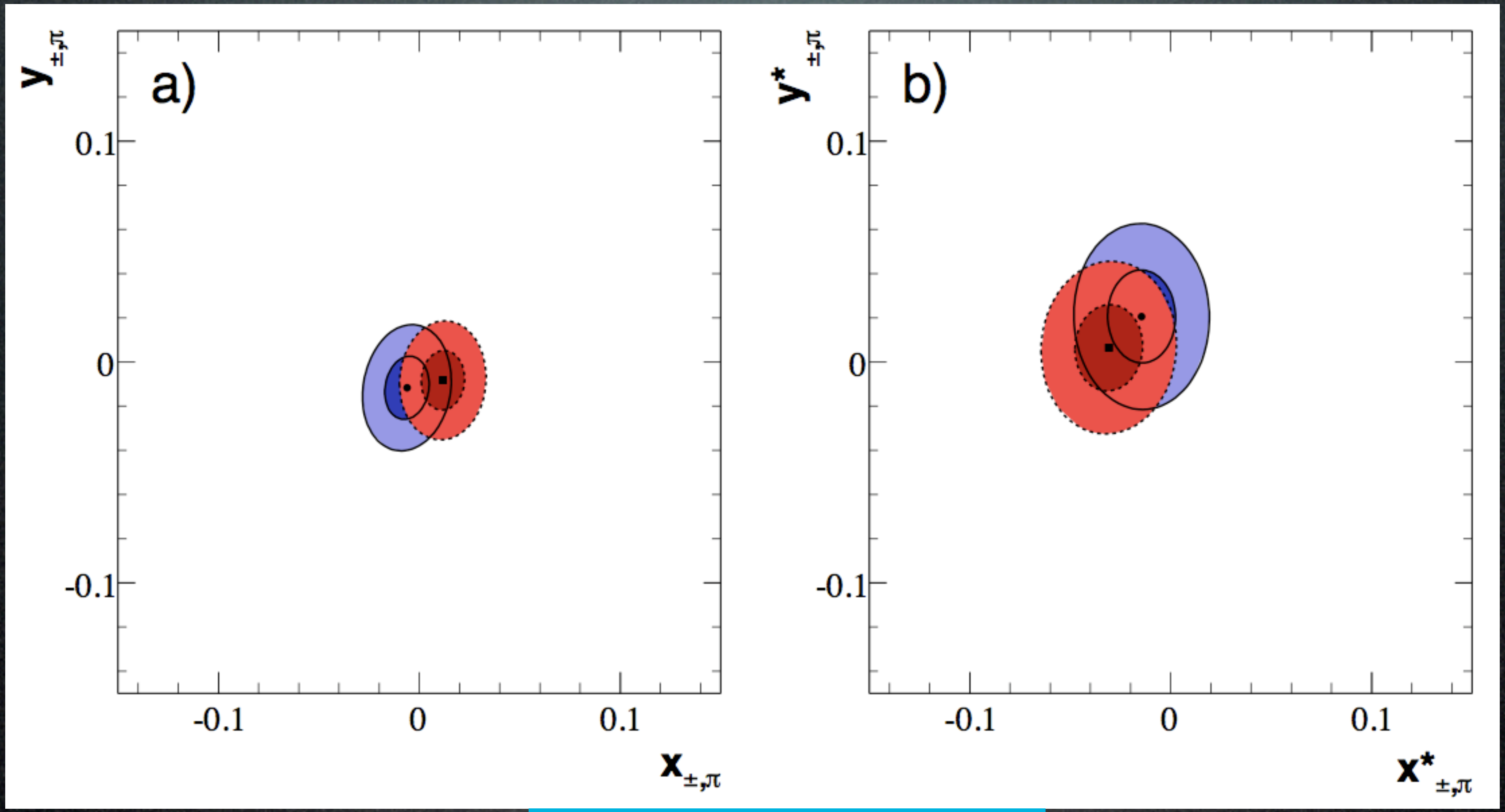
$$\mathcal{A}^{(*)}_{\mp}(m_-^2, m_+^2) \propto \mathcal{A}_{D\mp} + \lambda r_B^{(*)} e^{i(\delta_B^{(*)} \mp \gamma)} \mathcal{A}_{D\pm}$$

$$\Gamma^{(*)}_{\mp}(m_-^2, m_+^2) \propto |A_{D\mp}|^2 + {r_B^{(*)}}^2 |A_{D\pm}|^2 + 2\lambda \left[x_{\mp}^{(*)} \Re\{A_{D\mp} A^*_{D\pm}\} + y_{\mp}^{(*)} \Im\{A_{D\mp} A^*_{D\pm}\} \right]$$

λ=+1 for $B \to D^0K$, $D^{*0}[D^0\pi^0]K$, D^0K^*
λ=-1 for $B \to D^{*0}[D^0\gamma]K$

Cross-checking the Dalitz CP fit

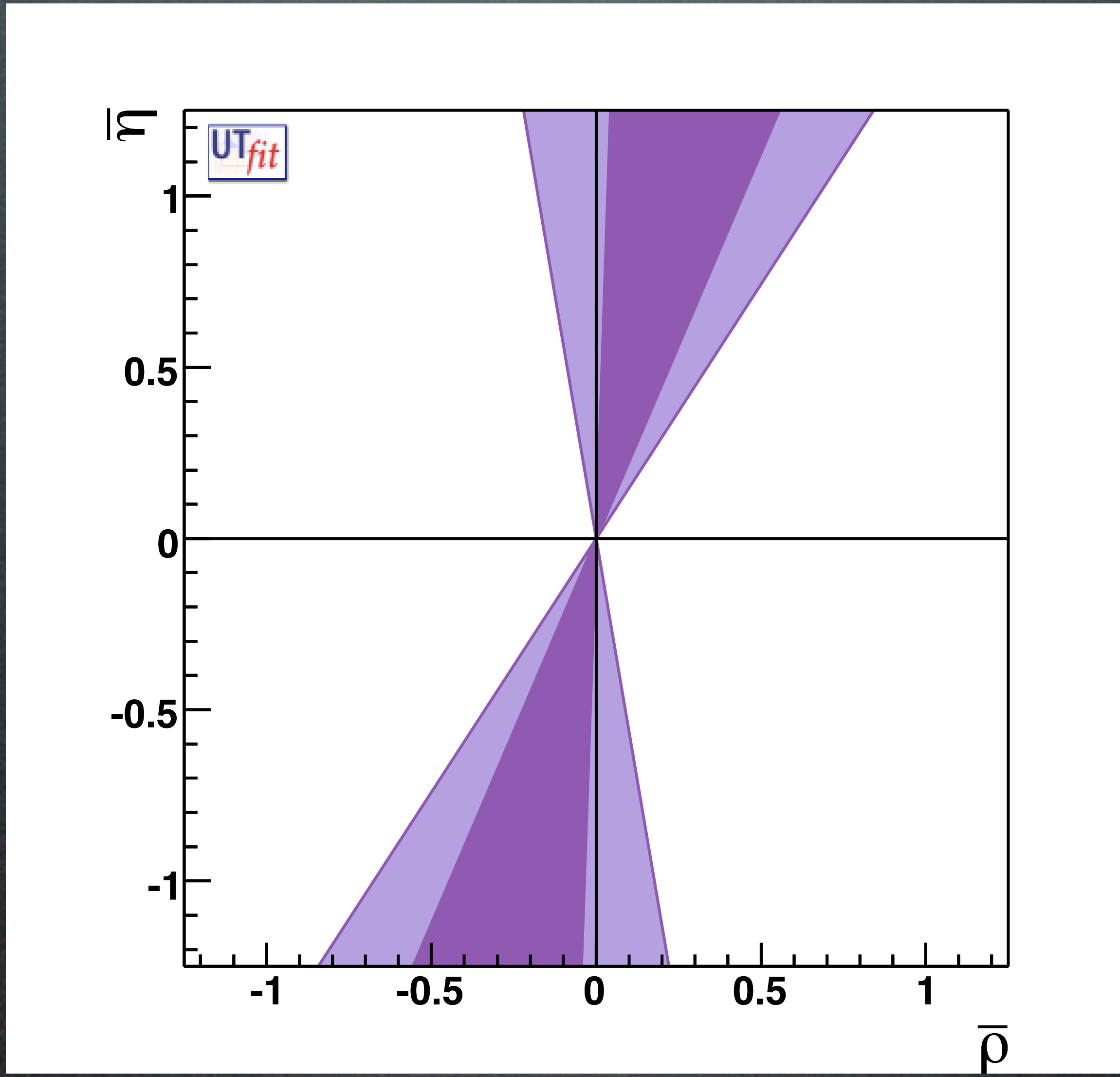
- The same analysis applied to the B->Dπ sample:



Consistent with zero

Constraining the γ angle

- Using the information from the various methods, channels and B decays it is possible to constrain γ and δ_B, r_B (UTfit Collaboration):



γ = 78 ± 12 ([54,102] @ 95% Prob.)

γ = -102 ± 16 ([-126,-78] @ 95% Prob.)